A Brief CDMA Background and Introduction to CDMA2000

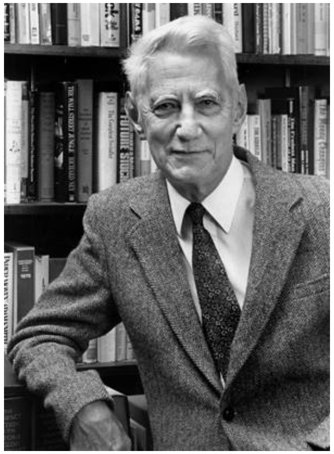
Purpose of This Module

- Some CDMA operators are implementing CDMA2000 1xRTT with the main intention of gaining more capacity for voice traffic
- The following pages provide streamlined CDMA basics from a capacity-driven point of view. These are the topics:
  - Spread Spectrum Principles - Capacity and Shannon's theorem
  - What we want 1xRTT to do for us
  - CDMA channelization and spreading details
  - CDMA code details review

CDMA Spread Spectrum Principles
Capacity: Shannon's Theorem

Claude Shannon:
The Einstein of Information Theory

- The core idea that makes CDMA possible was first explained by Claude Shannon, a Bell Labs research mathematician
- Shannon's work relates amount of information carried, channel bandwidth, signal-to-noise-ratio, and detection error probability
  - It shows the theoretical upper limit attainable



In 1948 **Claude Shannon** published his landmark paper on information theory, ***A Mathematical Theory of Communication***. He observed that "the fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point." His paper so clearly established the foundations of information theory that his framework and terminology are standard today. Shannon died Feb. 24, 2001, at age 84.

SHANNON'S CAPACITY EQUATION

$$C = B_{\omega} \log_2 \left[1 + \frac{S}{N} \right]$$

B_{ω} = bandwidth in Hertz
C = channel capacity in bits/second
S = signal power
N = noise power

Perspective on CDMA Today

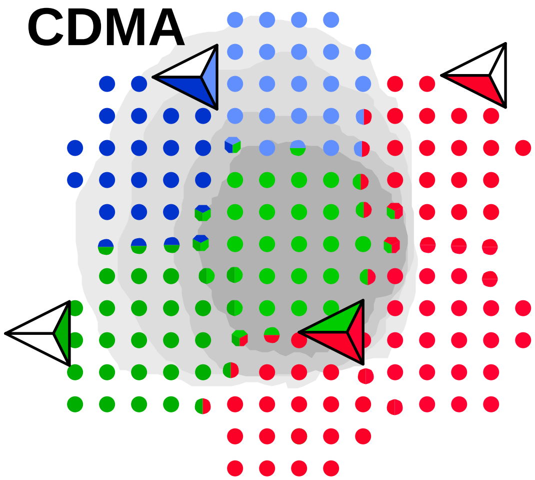
- On one carrier of one sector of an IS-95 CDMA BTS today, we sometimes see peak loadings of roughly 40 users
- What's the actual payload in user bits?
  - Suppose they're using EVRC vocoders, max 9600 bps
  - Average per-user bit rate roughly 6800 bps
  - Total payload carried = 40 x 6800 = about 272 Kbps
- The chip rate of the CDMA signal is 1,228,800 and the bandwidth of the signal is about 1,228,800 Hz.
  - So the information per hertz of bandwidth is about 272K/1228K, or about 1/4 bit per hertz of bandwidth
- The spreading gain is about 1228K/272K, roughly 4 which is 6 db
  - That's the "cushion" that keeps the system working well!

What 1xRTT Offers

- Today's IS-95 CDMA uses QPSK modulation, but actually transmits duplicate copies of each user's total information on both the I and Q phase planes
  - In essence, this is BPSK modulation!
  - There's not much value or benefit, since in fading or interference, both I and Q are simultaneously impaired!
- By transmitting only one copy of a user's information -- half of it on I and half of it on Q - theoretically double the information content can be carried in the 1xRTT CDMA signal -- true QPSK!
  - This roughly doubles the number of voice users we can carry
  - But any old IS-95 users will still continue to occupy "double space" in the signal as before
  - The percentages of IS-95 and 1xRTT users will determine the actual benefit to be obtained
- 1xRTT also provides new types of channels for fast packet data, but it's the operator's choice whether or not to exploit data or just to enjoy increased voice capacity
- In 1xRTT, capacity of one sector/one carrier becomes roughly 540 Kbps

CDMA: Using A New Dimension

- CDMA at first seems very strange when compared with 'normal' radio technologies
- Every sector of every base station transmits simultaneously on the same frequency
  - Not separated onto different frequencies, and not on different timeslots
- The signal of a CDMA BTS sector carries all its individual channels simultaneously
  - Not separated into timeslots, not separated onto different frequencies
- All mobiles are transmitting simultaneously on their own frequency
  - Not on different frequencies as in FDMA
  - Not on different timeslots as in TDMA
- How is it possible to distinguish the channels of individual users?!!?



The Secret of CDMA

•Each CDMA user has a unique code pattern, different from the code pattern of any other user in the area. The user's actual "payload" information bits are combined with a much faster, yet unique, "noise" waveform.

•At the receiver, the received signal is combined with the same "noise" waveform locally generated. What is left is the user's information bits.

•Since all users' noise waveforms are random compared to each other, the presence of other users' signals does not confuse the detection process.

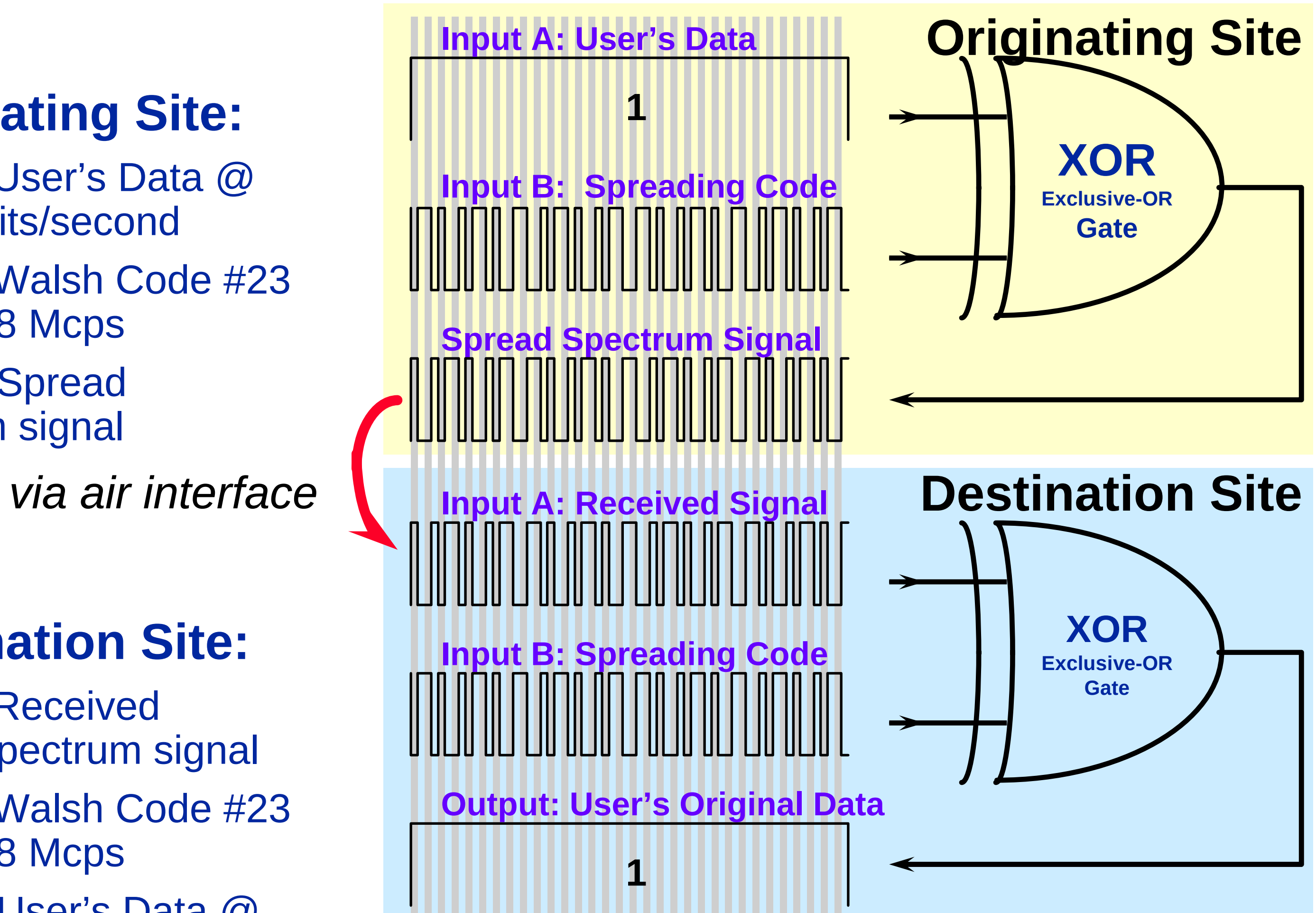
The Mechanics of DSSS Spreading: Viewed as Waveforms in Time

At Originating Site:

- Input A: User's Data @ 19,200 bits/second
- Input B: Walsh Code #23 @ 1.2288 Mcps
- Output: Spread spectrum signal

At Destination Site:

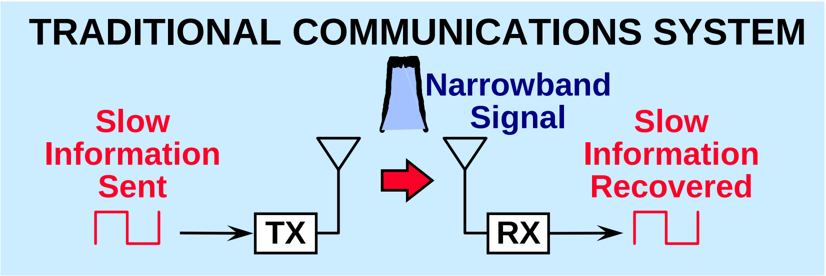
- Input A: Received spread spectrum signal
- Input B: Walsh Code #23 @ 1.2288 Mcps
- Output: User's Data @ 19,200 bits/second just as originally sent

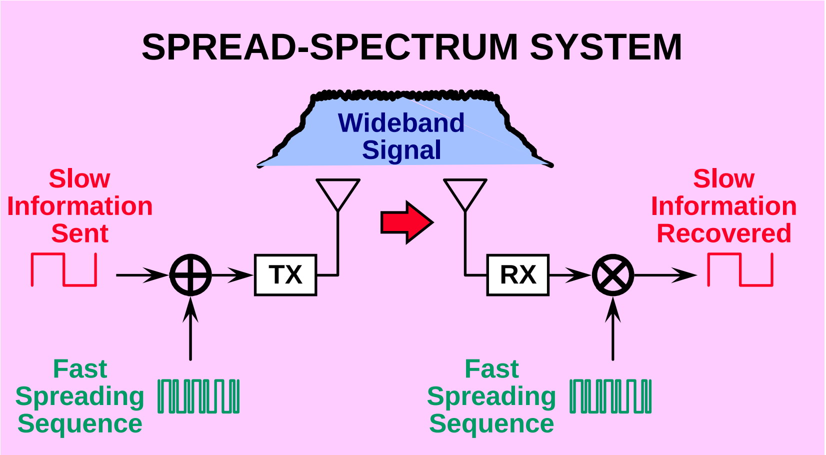


Drawn to actual scale and time alignment

Direct-Sequence Spreading Viewed as Frequency Spectra

- Traditional technologies try to squeeze a user's signal into a minimum required bandwidth
- CDMA uses larger bandwidth but exploits the resulting processing gain to get capacity





Spread Spectrum Payoff:
Processing Gain

The CDMA Spread Spectrum Payoff:
Would you like a lump-sum, or monthly payments?

- Shannon's work suggests that a certain bit rate of information deserves a certain bandwidth
- If one CDMA user is carried alone by a CDMA signal, the processing gain is large - roughly 21 db for an 8k vocoder.
  - Each doubling of the number of users consumes 3 db of the processing gain
  - Somewhere above 32 users, the signal-to-noise ratio becomes undesirable and the ultimate capacity of the sector is reached
- Practical CDMA systems restrict the number of users per sector to ensure processing gain remains at usable levels

CDMA Spreading Gain

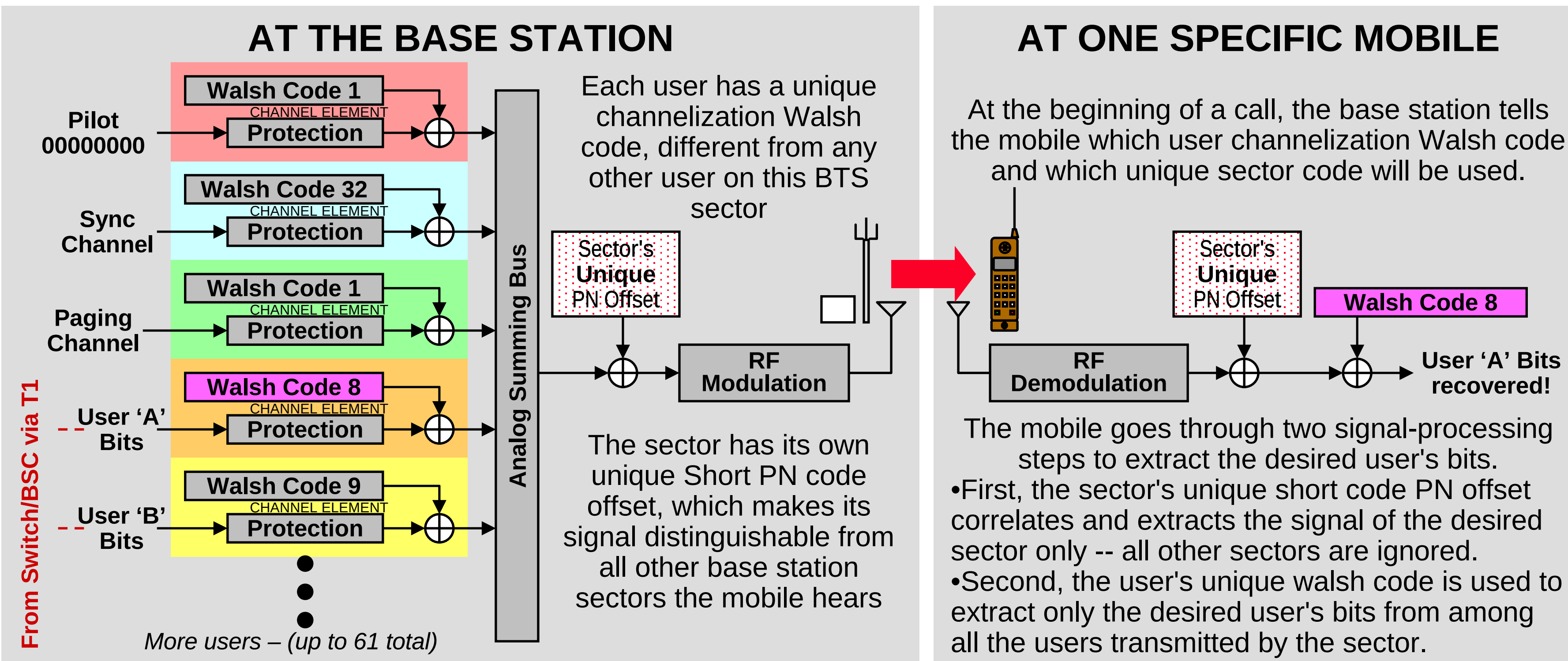
Consider a user with a 9600 bps vocoder talking on a CDMA signal 1,228,800 hz wide. The processing gain is 1228800/9600 = 128, which is 21 db. What happens if additional users are added?

# Users	Processing Gain
1	21 db
2	18 db
4	15 db
8	12 db
16	9 db
32	6 db
64.....Uh, Regis, can I just take the money I've already won, and go home now?	

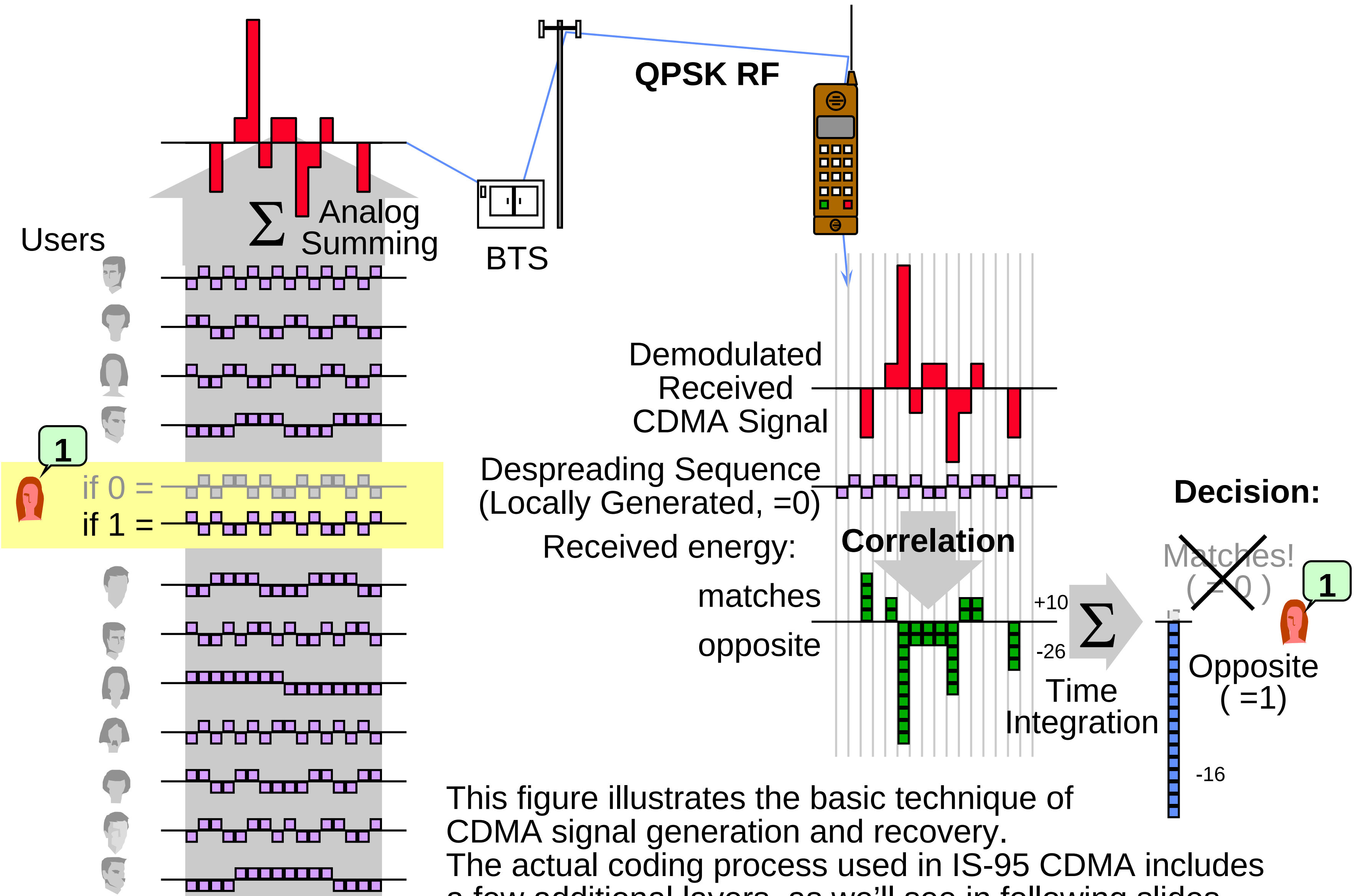
Real-World
CDMA Channel Coding

Real-World CDMA Codes - Forward Link

- In actual commercial systems, a user's unique code is actually constructed from a combination several simpler codes
- A base station uses a different unique channelization code to mix with and encode the signal of each individual user before combining their signals
- The combined signal is then coded with a unique pattern to distinguish this sector's signal from any the signals of other sectors
- Notice one base station sector can carry the channels of many users



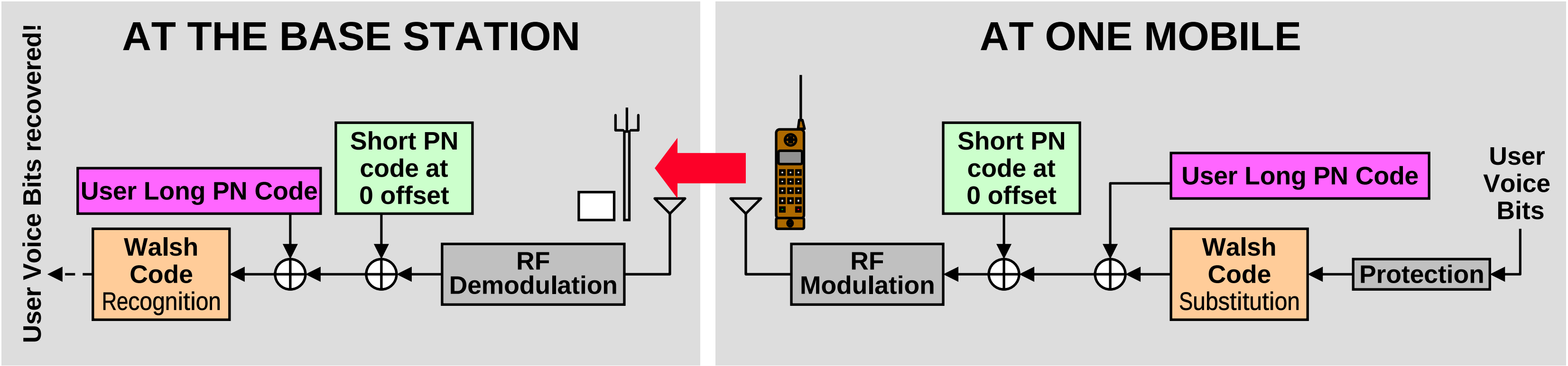
How a BTS Sector Serves Multiple Users



This figure illustrates the basic technique of CDMA signal generation and recovery.
The actual coding process used in IS-95 CDMA includes a few additional layers, as we'll see in following slides.

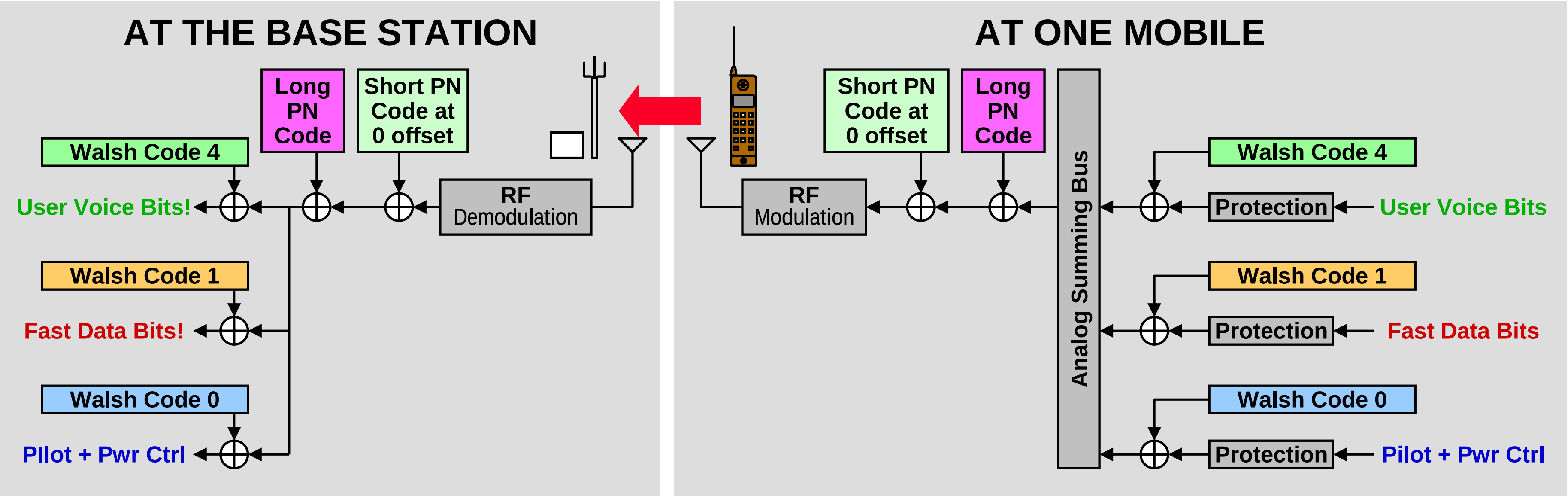
Real-World CDMA Codes - Reverse Link

- Each mobile has a unique CDMA code pattern which makes its signal different from the signal of any other mobile nearby
  - In North American CDMA, the unique code is computed using the phone's serial number, so each phone in the world has a different code
- Bits the mobile transmits are first protected by error-resistant coding, then combined with the mobile's unique CDMA code
  - Phase modulation is then performed and the signal is transmitted
- At the base station, the RF signals of all nearby mobiles are received
  - Each mobile's signal is extracted by an individual circuit ('channel element') which generates the mobile's unique code



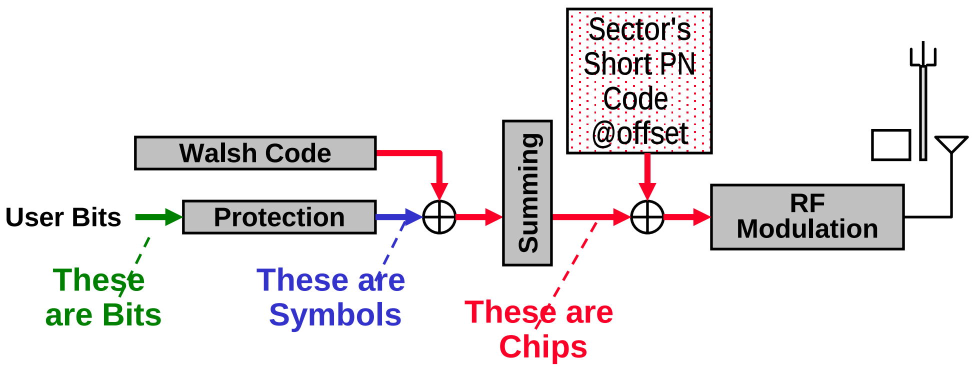
Special Reverse Link Coding for 3G

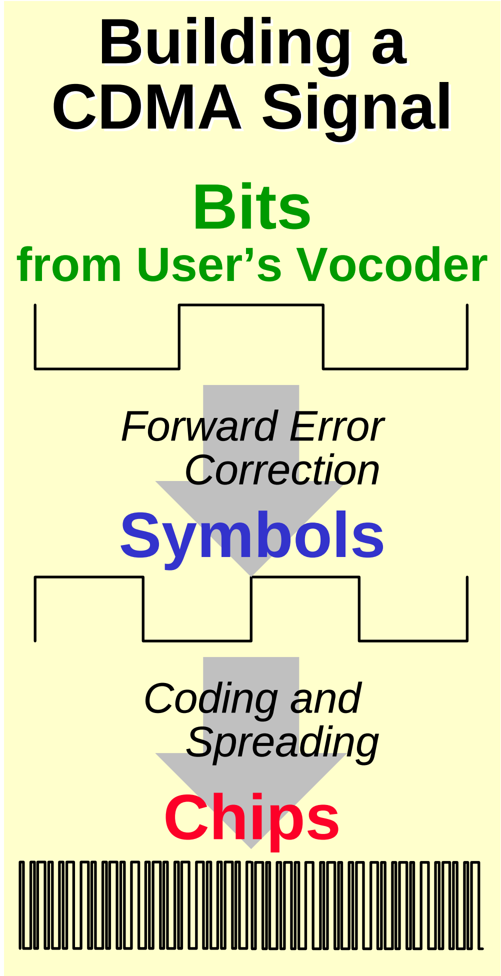
- In 3G systems, links sometimes includes multiple channels of one user
  - A fundamental channel carrying voice or medium-speed data
  - One or more supplemental channels carrying fast data
  - A dedicated control channel carrying messaging and power control
- The base station is already capable of transmitting multiple channels, so no new tricks are required
- A 3G mobile can use separate additional channelization codes, and possible independent transmission on its I and Q phase planes
  - 3G mobiles may be transmitting several types of channels at once



Bits, Symbols, and Chips
Not All 'Bits' are Equally Famous and Important

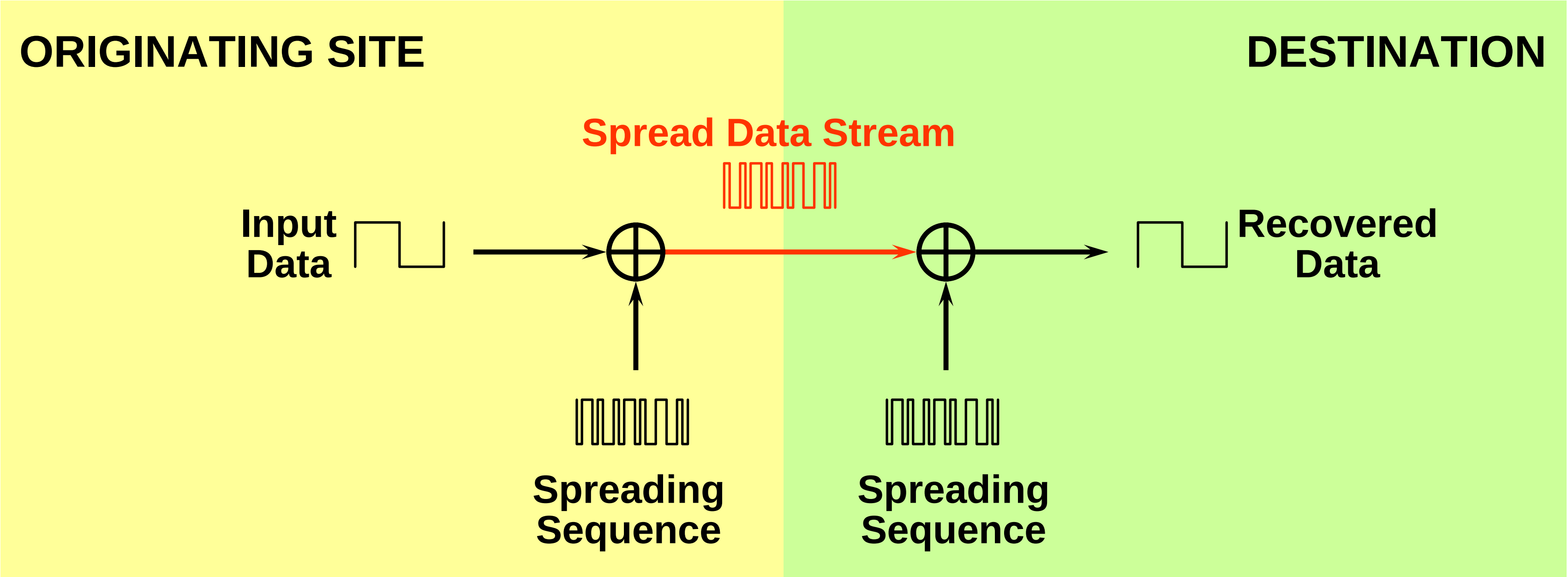
- The raw information is in the form of bits
- Bits are protected by error-correcting redundant coding, producing a bigger population of more-rugged 1s and 0s called symbols
- The symbols are combined with individual 1s and 0s of CDMA codes - these are called chips





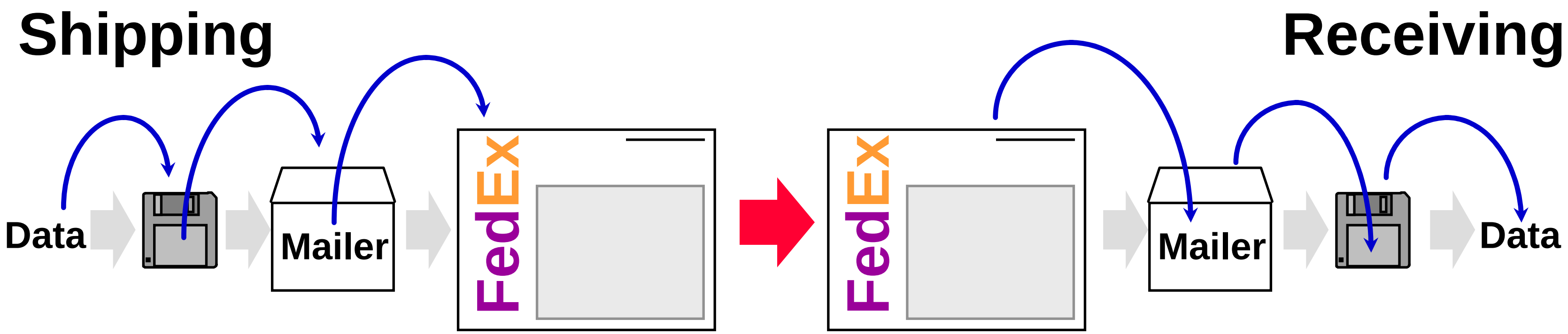
IS-95 CDMA
Codes and Channels

Spreading: What we do, we can undo



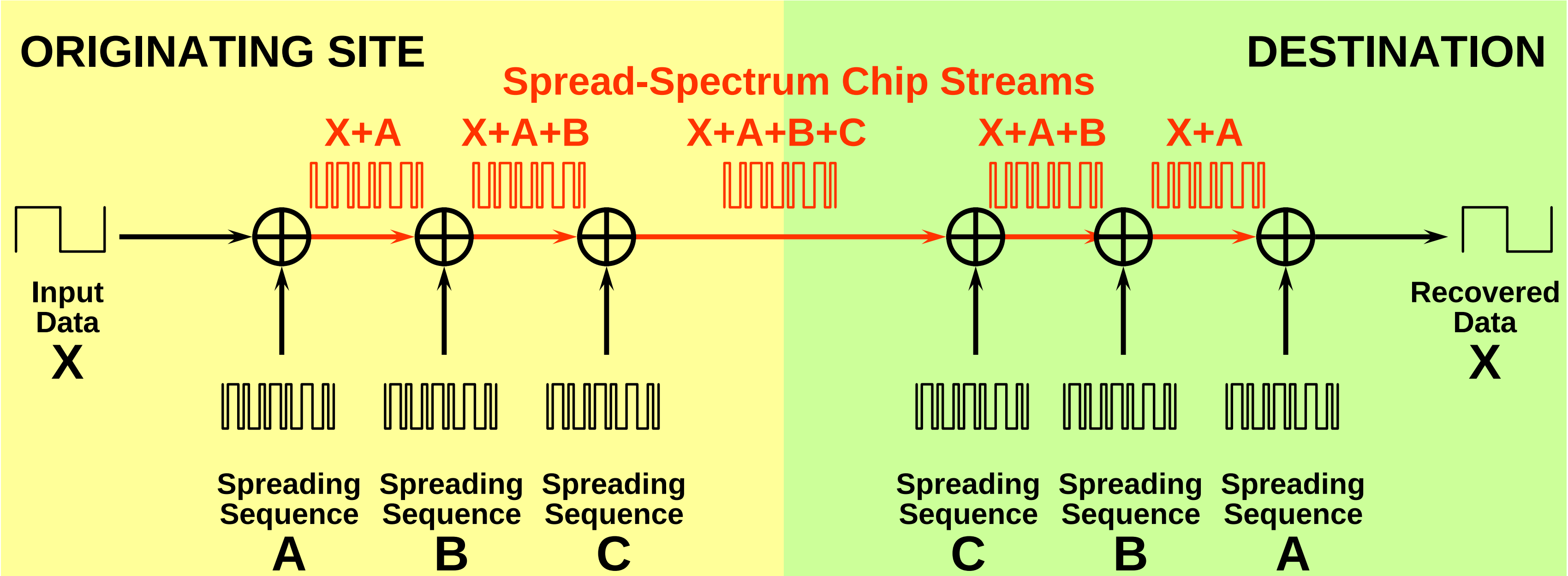
- Sender combines data with a fast spreading sequence, transmits spread data stream
- Receiver intercepts the stream, uses same spreading sequence to extract original data

“Shipping and Receiving” via CDMA



- Whether in shipping and receiving, or in CDMA, packaging is extremely important!
- Cargo is placed inside “nested” containers for protection and to allow addressing
- The shipper packs in a certain order, and the receiver unpacks in the reverse order
- CDMA “containers” are spreading codes

CDMA's Nested Spreading Sequences



- CDMA combines three different spreading sequences to create unique, robust channels
- The sequences are easy to generate on both sending and receiving ends of each link
- "What we do, we can undo"

One of the CDMA Spreading Sequences: Walsh Codes

- 64 “Magic” Sequences, each 64 chips long
- Each Walsh Code is precisely Orthogonal with respect to all other Walsh Codes
  - it’s simple to generate the codes, or
  - they’re small enough to use from ROM

Unique Properties:
Mutual Orthogonality

EXAMPLE:

Correlation of Walsh Code #23 with Walsh Code #59

```
#23   0110100101101001100101101001011001101001011010011001011010010110
#59   0110011010011001100110010110011010011001011001100110011010011001
Sum   0000111111110000000011111111000011110000000011111111000000001111
```

Correlation Results: 32 1’s, 32 0’s: Orthogonal!!

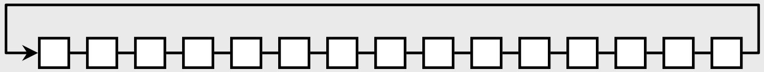
WALSH CODES

#	64-Chip Sequence
0	0000000000000000000000000000000000000000000000000000000000000000
1	0101010101010101010101010101010101010101010101010101010101010101
2	0011001100110011001100110011001100110011001100110011001100110011
3	0110011001100110011001100110011001100110011001100110011001100110
4	0000111100001111000011110000111100001111000011110000111100001111
5	0101101001011010010110100101101001011010010110100101101001011010
6	0011110000111100001111000011110000111100001111000011110000111100
7	0110100101101001011010010110100101101001011010010110100101101001
8	0000000011111111000000001111111100000000111111110000000011111111
9	0101010110101010010101011010101001010101101010100101010110101010
10	0011001111001100001100111100110000110011110011000011001111001100
11	0110011010011001011001101001100101100110100110010110011010011001
12	0000111111110000000011111111000000001111111100000000111111110000
13	0101101010100101010110101010010101011010101001010101101010100101
14	0011110011000011001111001100001100111100110000110011110011000011
15	0110100110010110011010011001011001101001100101100110100110010110
16	0000000000000000111111111111111100000000000000001111111111111111
17	0101010101010101101010101010101001010101010101011010101010101010
18	0011001100110011110011001100110000110011001100111100110011001100
19	0110011001100110100110011001100101100110011001101001100110011001
20	0000111100001111111100001111000000001111000011111111000011110000
21	0101101001011010101001011010010101011010010110101010010110100101
22	0011110000111100110000111100001100111100001111001100001111000011
23	0110100101101001100101101001011001101001011010011001011010010110
24	0000000011111111111111110000000000000000111111111111111100000000
25	0101010110101010101010100101010101010101101010101010101001010101
26	0011001111001100110011000011001100110011110011001100110000110011
27	0110011010011001100110010110011001100110100110011001100101100110
28	0000111111110000111100000000111100001111111100001111000000001111
29	0101101010100101101001010101101001011010101001011010010101011010
30	0011110011000011110000110011110000111100110000111100001100111100
31	0110100110010110100101100110100101101001100101101001011001101001
32	0000000000000000000000000000000011111111111111111111111111111111
33	0101010101010101010101010101010110101010101010101010101010101010
34	0011001100110011001100110011001111001100110011001100110011001100
35	0110011001100110011001100110011010011001100110011001100110011001
36	0000111100001111000011110000111111110000111100001111000011110000
37	0101101001011010010110100101101010100101101001011010010110100101
38	0011110000111100001111000011110011000011110000111100001111000011
39	0110100101101001011010010110100110010110100101101001011010010110
40	0000000011111111000000001111111111111111000000001111111100000000
41	0101010110101010010101011010101010101010010101011010101001010101
42	0011001111001100001100111100110011001100001100111100110000110011
43	0110011010011001011001101001100110011001011001101001100101100110
44	0000111111110000000011111111000011110000000011111111000000001111
45	0101101010100101010110101010010110100101010110101010010101011010
46	0011110011000011001111001100001111000011001111001100001100111100
47	0110100110010110011010011001011010010110011010011001011001101001
48	0000000000000000111111111111111111111111111111110000000000000000
49	0101010101010101101010101010101010101010101010100101010101010101
50	0011001100110011110011001100110011001100110011000011001100110011
51	0110011001100110100110011001100110011001100110010110011001100110
52	0000111100001111111100001111000011110000111100000000111100001111
53	0101101001011010101001011010010110100101101001010101101001011010
54	0011110000111100110000111100001111000011110000110011110000111100
55	0110100101101001100101101001011010010110100101100110100101101001
56	0000000011111111111111110000000011111111000000000000000011111111
57	0101010110101010101010100101010110101010010101010101010110101010
58	0011001111001100110011000011001111001100001100110011001111001100
59	0110011010011001100110010110011010011001011001100110011010011001
60	0000111111110000111100000000111111110000000011110000111111110000
61	0101101010100101101001010101101010100101010110100101101010100101
62	0011110011000011110000110011110011000011001111000011110011000011
63	0110100110010110100101100110100110010110011010010110100110010110

Other Sequences: Generation & Properties

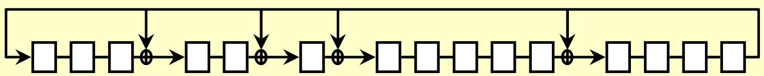
- Other CDMA sequences are generated in shift registers
- Plain shift register: no fun, sequence = length of register
- Tapped shift register generates a wild, self-mutating sequence 2^N-1 chips long (N=register length)
  - Such sequences match if compared in step (no-brainer, any sequence matches itself)
  - Such sequences appear approximately orthogonal if compared with themselves not exactly matched in time
  - false correlation typically <2%

An Ordinary Shift Register



Sequence repeats *every **N** chips,* where N is number of cells in register

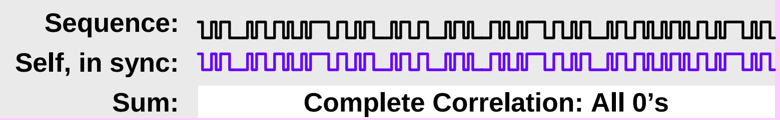
A Tapped, Summing Shift Register



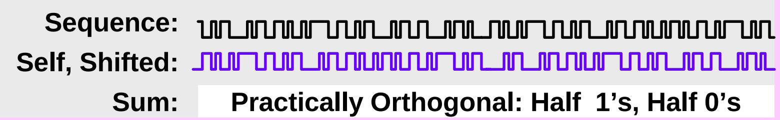
Sequence repeats *every* ***2^N-1*** *chips,* where N is number of cells in register

A Special Characteristic of Sequences Generated in Tapped Shift Registers

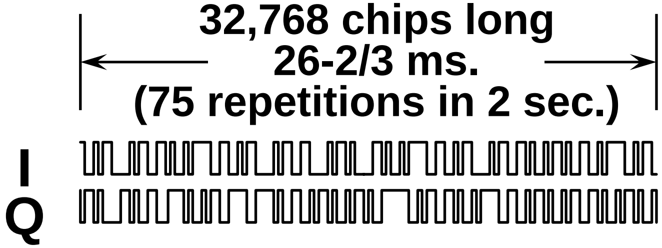
Compared In-Step: Matches Itself



Compared Shifted: Little Correlation

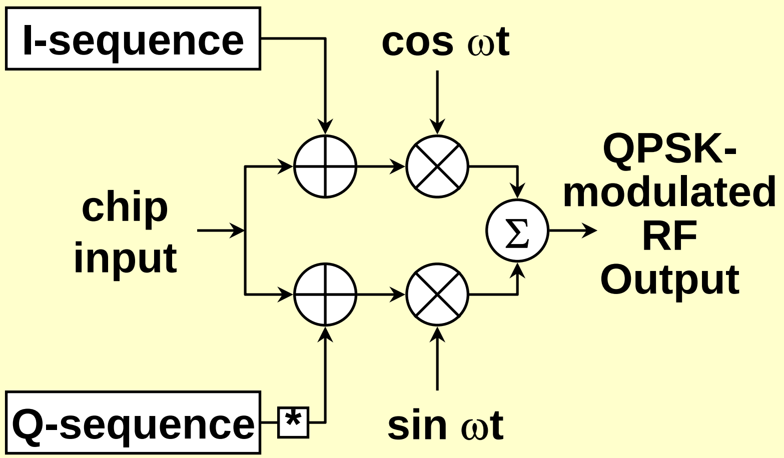


Another CDMA Spreading Sequence: The Short PN Code



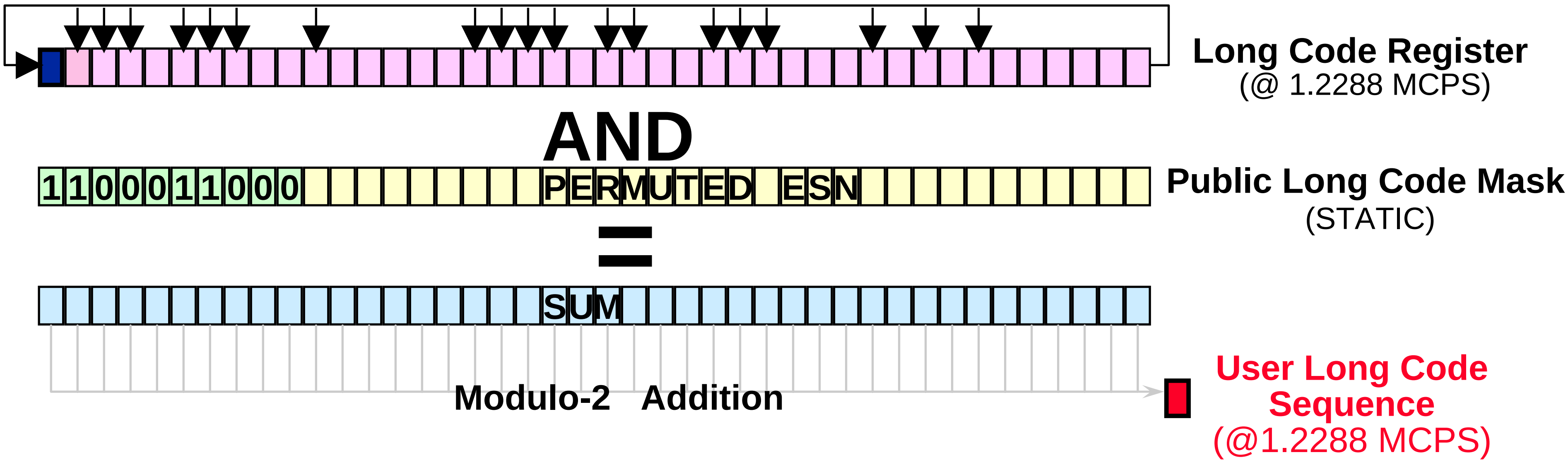
- The short PN code consists of two PN Sequences, I and Q, each 32,768 chips long
  - Generated in similar but differently-tapped 15-bit shift registers
  - They’re always used together, modulating the two phase axes of a QPSK modulator

CDMA QPSK Phase Modulator Using I and Q PN Sequences



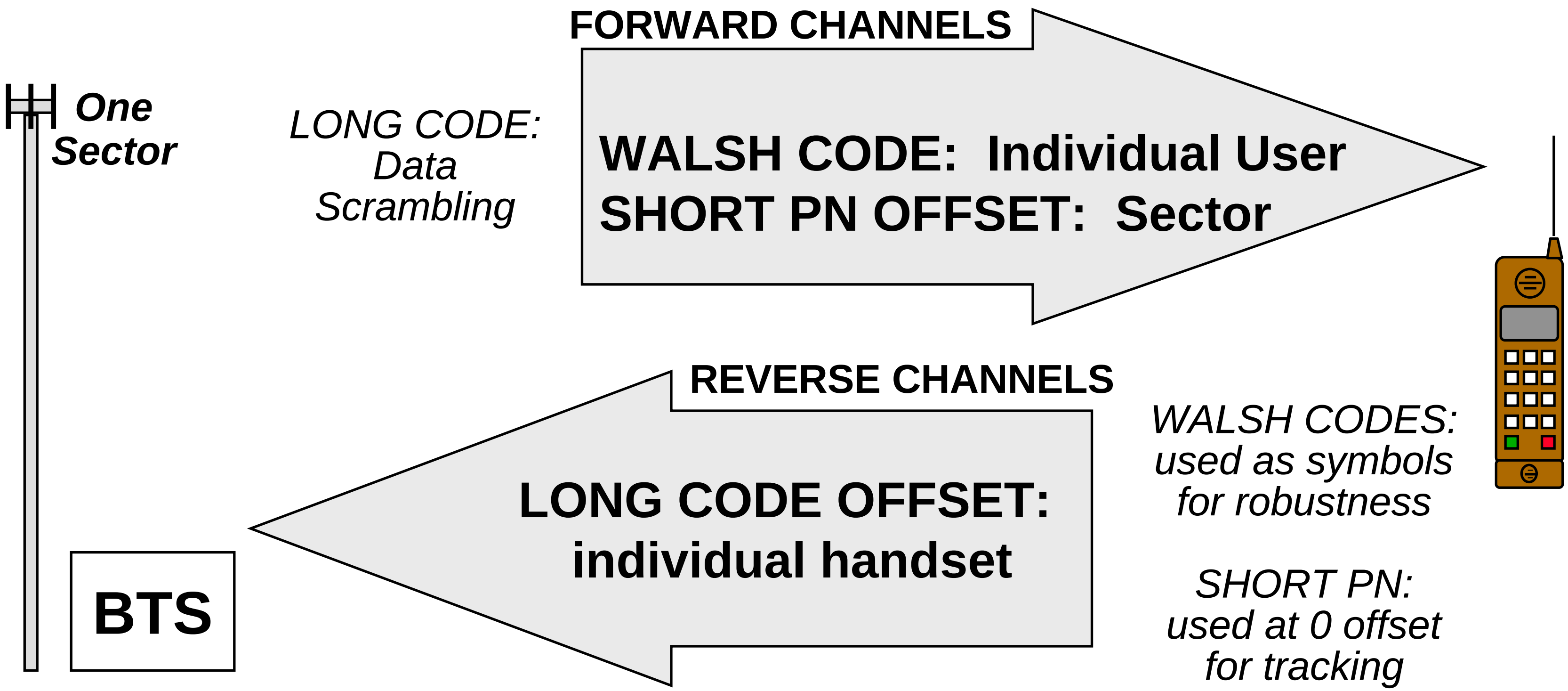
* In BTS, I and Q are used in-phase. In handset, Q is delayed 1/2 chip to avoid zero-amplitude crossings which would require a linear power amplifier

Third CDMA Spreading Sequence: Long Code
Generation & Masking to establish Offset



- Generated in a 42-bit register, the PN Long code is more than 40 days long (~4x10^{13} chips) -- too big to store in ROM in a handset, so it's generated chip-by-chip using the scheme shown above
- Each handset codes its signal with the PN Long Code, but at a unique offset computed using its ESN (32 bits) and 10 bits set by the system
  - this is called the "Public Long Code Mask"; produces unique shift
  - private long code masks are available for enhanced privacy
- Integrated over a period even as short as 64 chips, phones with different PN long code offsets will appear practically orthogonal

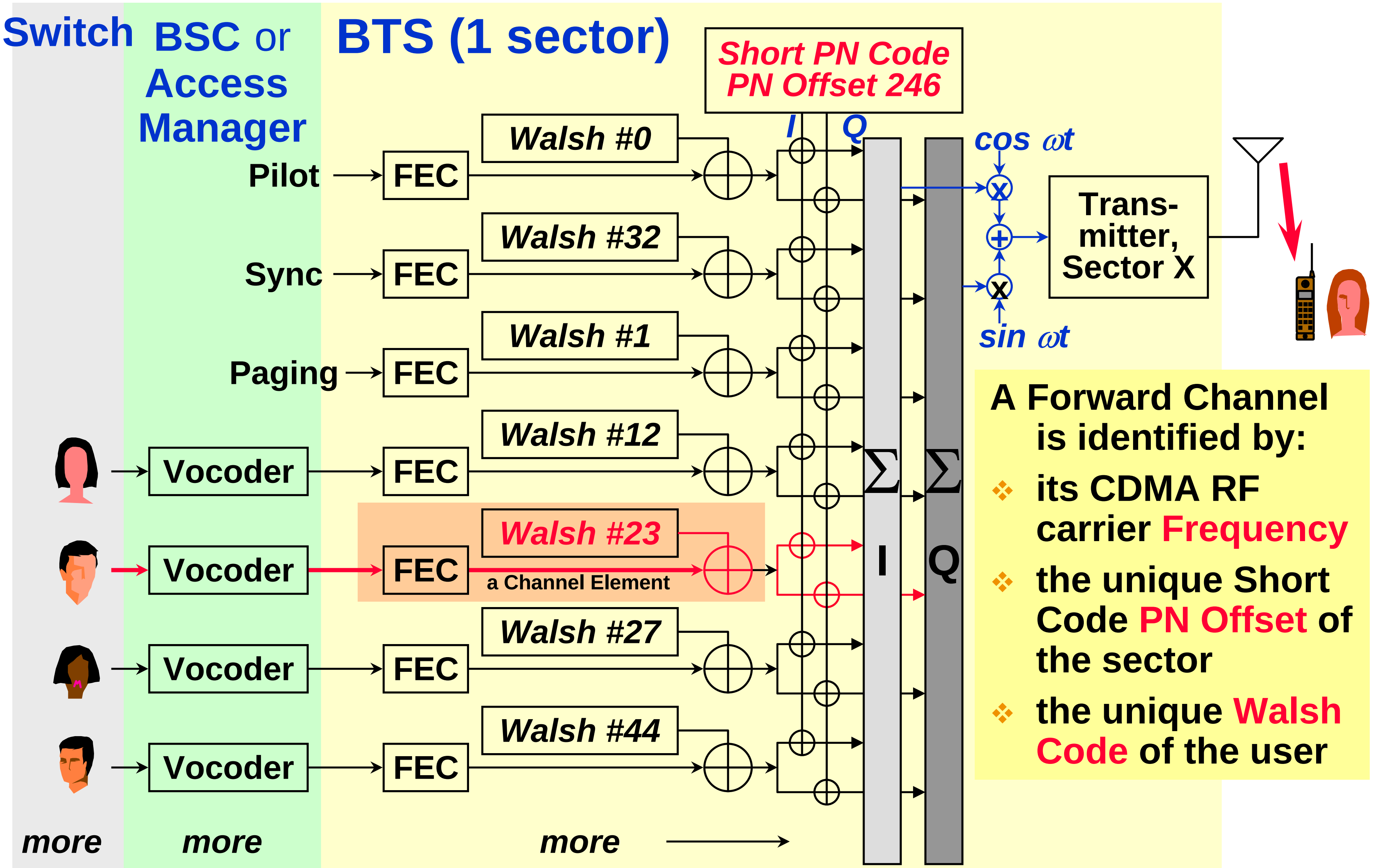
North American IS-95 CDMA Coding Summary



- The three spreading codes are used in different ways to create the forward and reverse links
- A forward channel exists by having a specific Walsh Code assigned to the user, and a specific PN offset for the sector
- A reverse channel exists because the mobile uses a specific offset of the Long PN sequence

IS-95 CDMA Forward and Reverse Channels

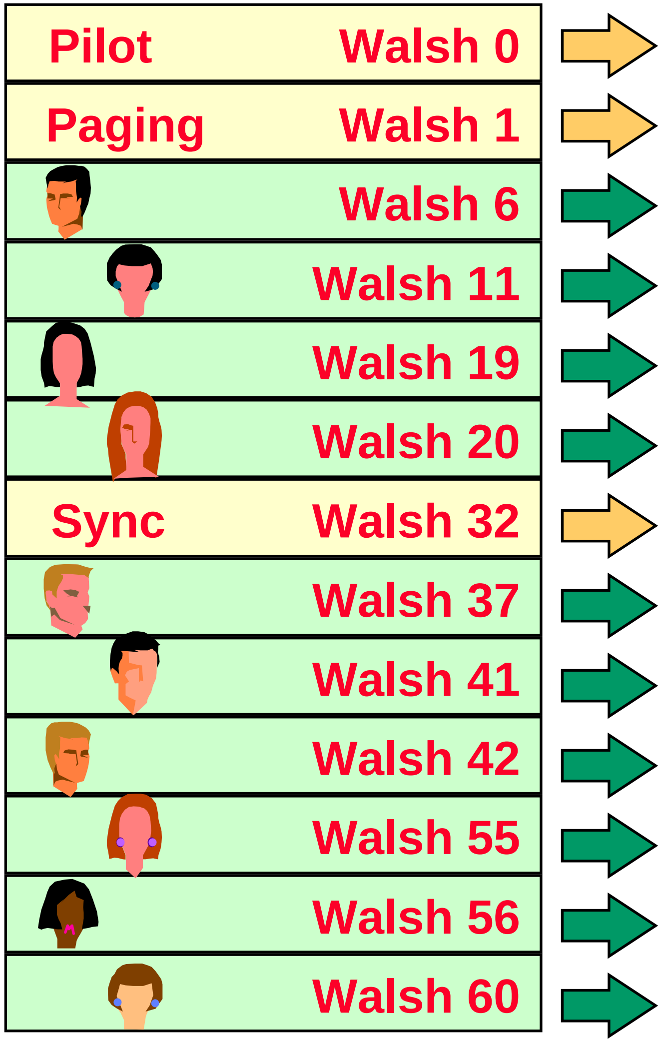
How a BTS Builds the Forward Code Channels



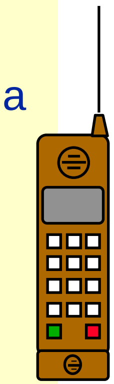
A Forward Channel is identified by:

- its CDMA RF carrier Frequency
- the unique Short Code PN Offset of the sector
- the unique Walsh Code of the user

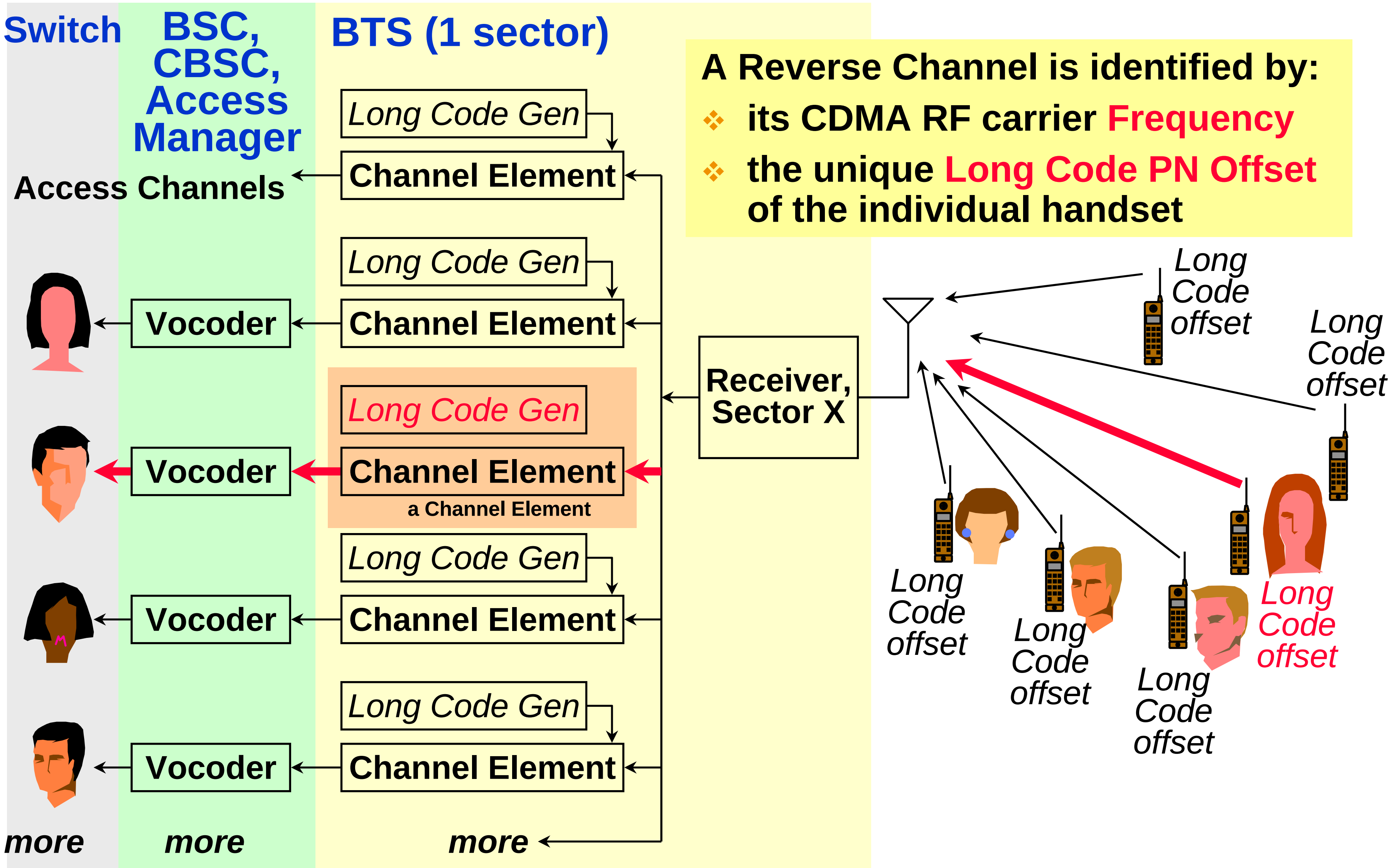
Functions of the CDMA Forward Channels



- **PILOT**: WALSH CODE **0**
  - The Pilot is a “structural beacon” which does not contain a character stream. It is a timing source used in system acquisition and as a measurement device during handoffs
- **SYNC**: WALSH CODE **32**
  - This carries a data stream of system identification and parameter information used by mobiles during system acquisition
- **PAGING**: WALSH CODES **1 up to 7**
  - There can be from one to seven paging channels as determined by capacity needs. They carry pages, system parameters information, and call setup orders
- **TRAFFIC**: any **remaining** WALSH codes
  - The traffic channels are assigned to individual users to carry call traffic. All remaining Walsh codes are available, subject to overall capacity limited by noise



Code Channels in the Reverse Direction

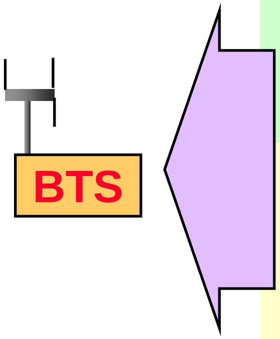


A Reverse Channel is identified by:

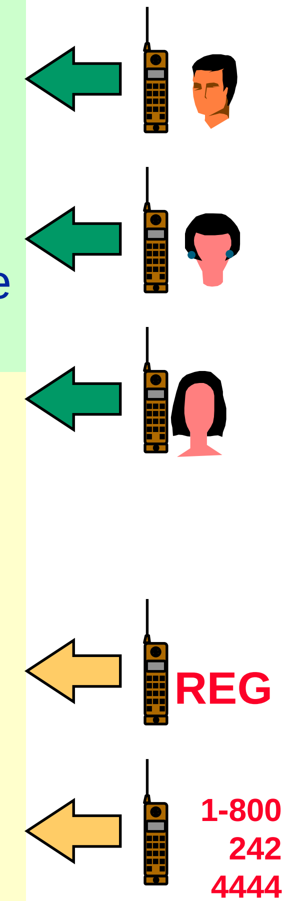
- **its CDMA RF carrier Frequency**
- **the unique Long Code PN Offset of the individual handset**

Functions of the CDMA Reverse Channels

There are two types of CDMA Reverse Channels:

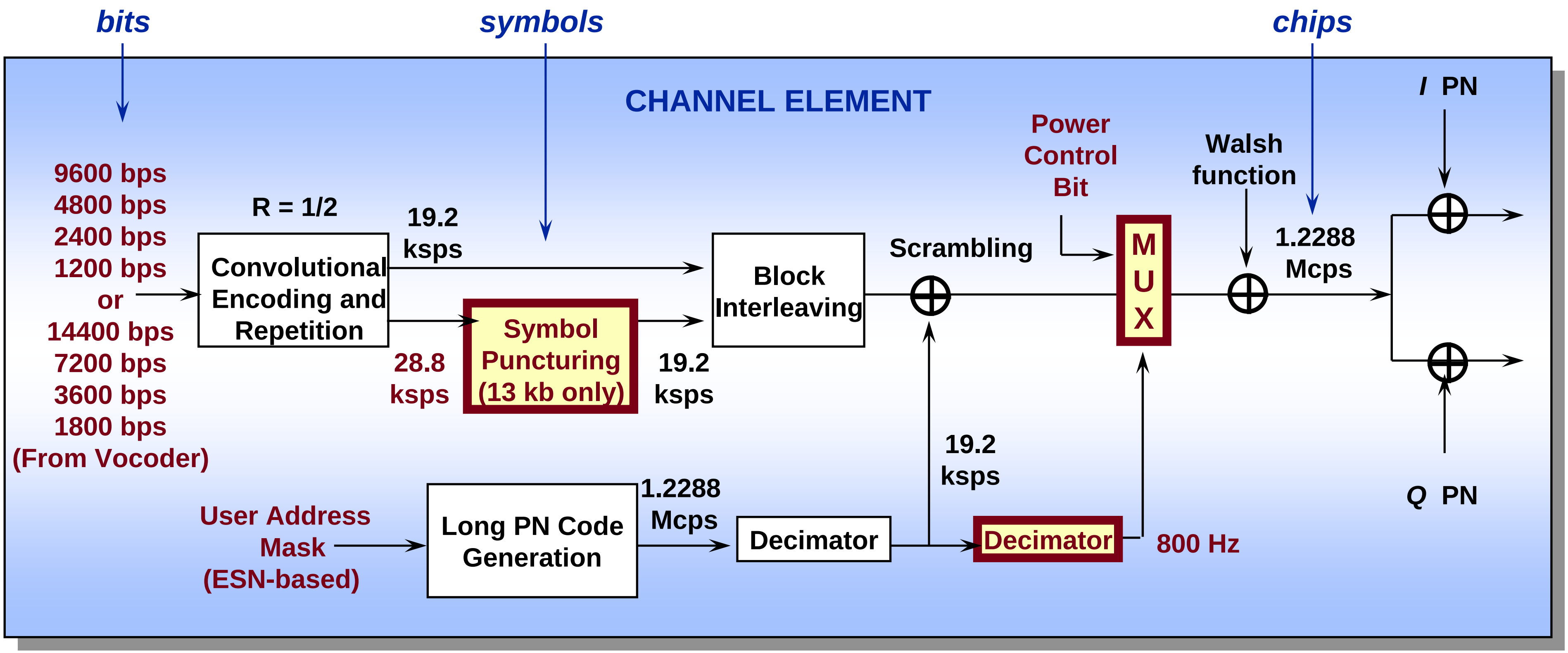


- **TRAFFIC CHANNELS** are used by individual users during their actual calls to transmit traffic to the BTS
  - a reverse traffic channel is really just a user-specific public or private Long Code mask
  - there are as many reverse Traffic Channels as there are CDMA phones in the world!
- **ACCESS CHANNELS** are used by mobiles not yet in a call to transmit registration requests, call setup requests, page responses, order responses, and other signaling information
  - an access channel is really just a public long code offset unique to the BTS sector
  - Access channels are paired to Paging Channels. Each paging channel can have up to 32 access channels.

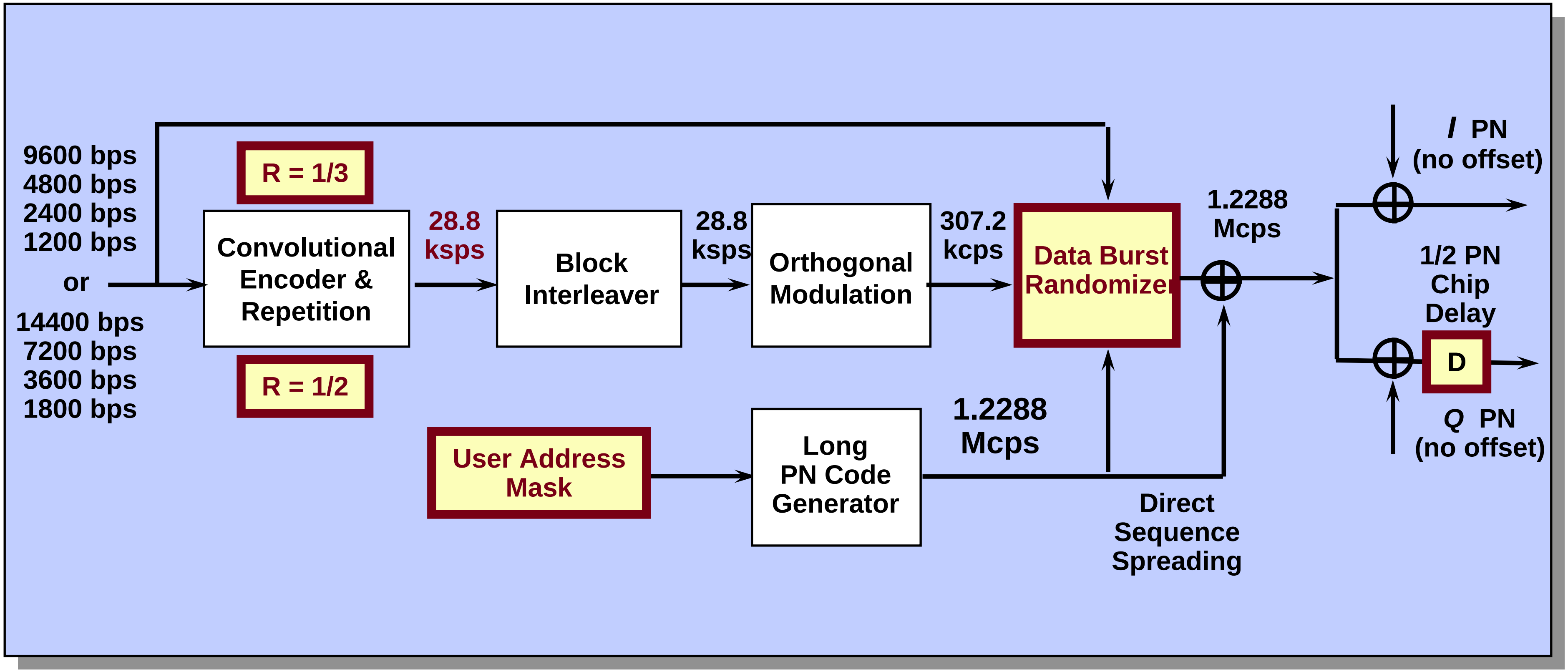


Although a sector can have up to seven paging channels, and each paging channel can have up to 32 access channels, nearly all systems today use only one paging channel per sector and only one access channel per paging channel.

Forward Traffic Channel: Generation Details from IS-95



Reverse Traffic Channel: Generation Details from IS-95

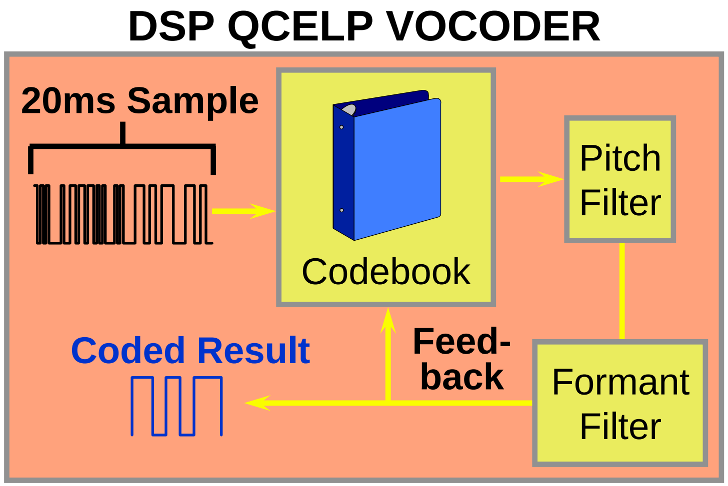


IS-95 Operational Details

Vocoding, Multiplexing, Power Control

Variable Rate Vocoding & Multiplexing

- Vocoders compress speech, reduce bit rate, greatly increasing capacity
- CDMA uses a superior Variable Rate Vocoder
  - full rate during speech
  - low rates in speech pauses
  - increased capacity
  - more natural sound
- Voice, signaling, and user secondary data may be mixed in CDMA frames

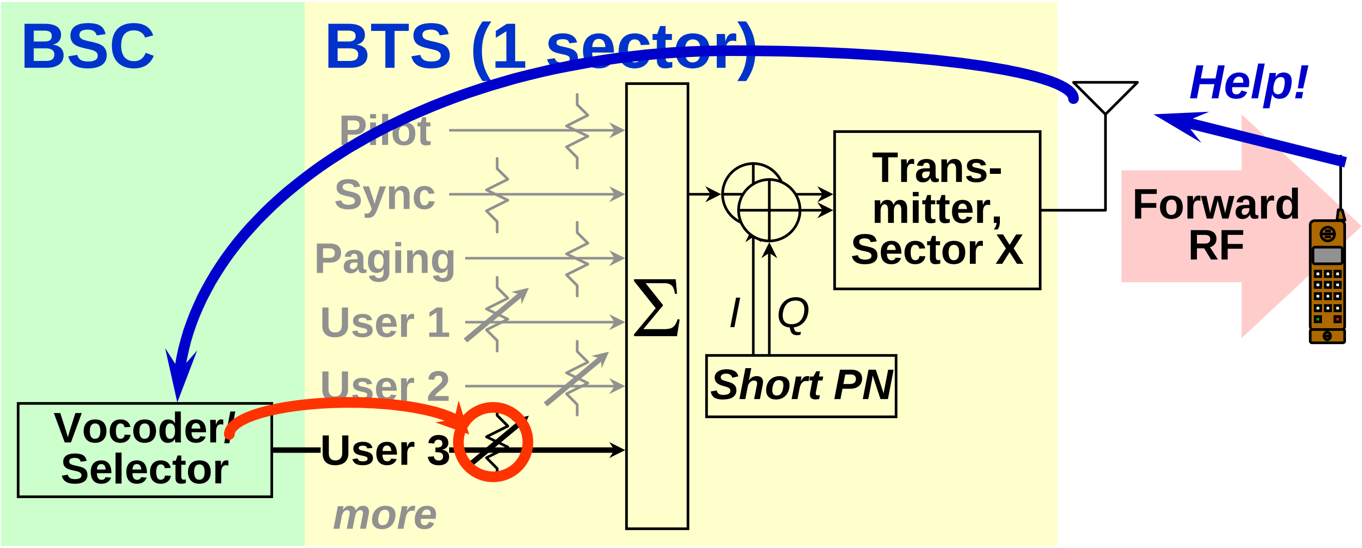


bits	Frame Sizes
288	Full Rate Frame
144	1/2 Rate Frame
72	1/4 Rt.
36	1/8

Frame Contents: can be a mixture of

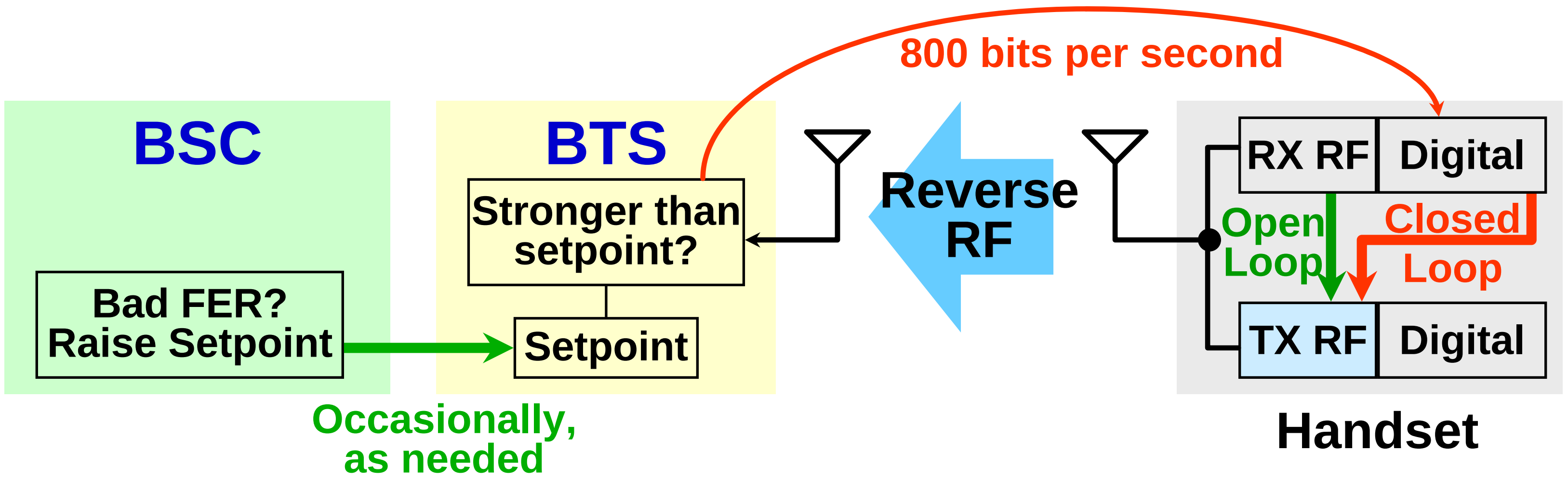
Primary Traffic (Voice or data)	**Signaling** (System Messaging)	**Secondary** (On-Air activation, etc)

Forward Power Control



- The BTS continually reduces the strength of each user's forward baseband chip stream
- When a particular handset sees errors on the forward link, it requests more energy
- The complainer's chip stream gets a quick boost; afterward, continues to diminish
- Each network manufacturer uses FER-based triggers and initial, minimum, and maximum traffic channel DGU values

Reverse Power Control



- Three methods work in tandem to equalize all handset signal levels at the BTS
  - Reverse *Open* Loop: handset adjusts power up or down based on received BTS signal (AGC)
  - Reverse *Closed* Loop: Is handset too strong? BTS tells up or down 1 dB 800 times/second
  - Reverse *Outer* Loop: BSC has FER trouble hearing handset? BSC adjusts BTS setpoint

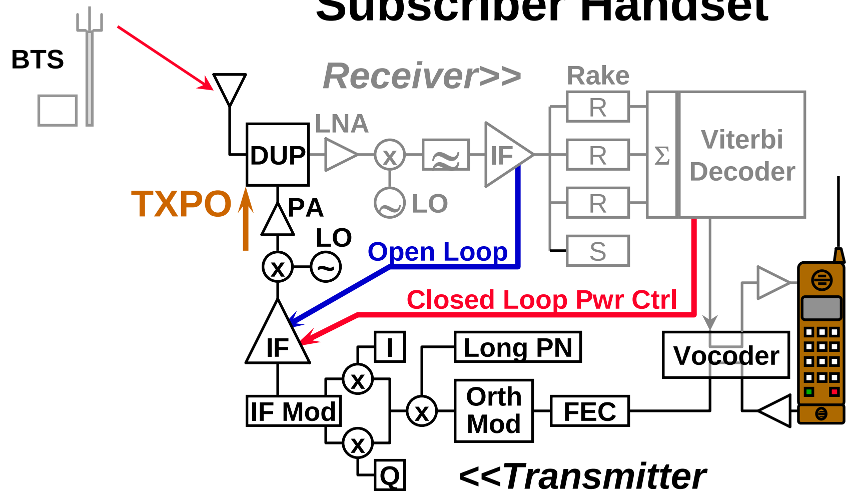
Details of Reverse Link Power Control

- **TXPO Handset Transmit Power**
  - Actual RF power output of the handset transmitter, including combined effects of **open loop power control** from receiver AGC *and* **closed loop power control** by BTS
  - can't exceed handset's maximum (typ. +23 dBm)

TXPO = -(RX$_{dbm}$) -C + TXGA
C = +73 for 800 MHz. systems
= +76 for 1900 MHz. systems

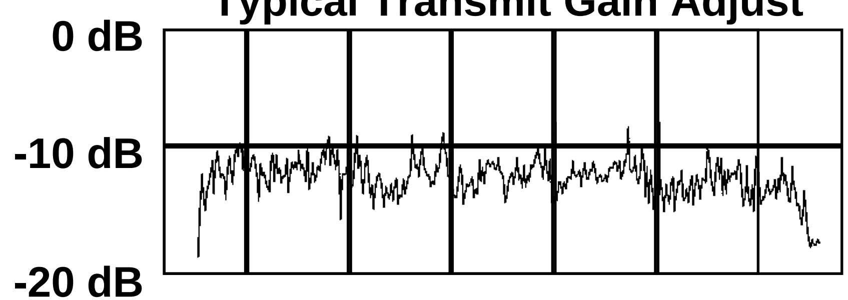
- **TXGA Transmit Gain Adjust**
  - Sum of all **closed-loop power control** commands from the BTS since the beginning of this call

Subscriber Handset



Typical TXPO:
+23 dBm in a coverage hole
0 dBm near middle of cell
-50 dBm up close to BTS

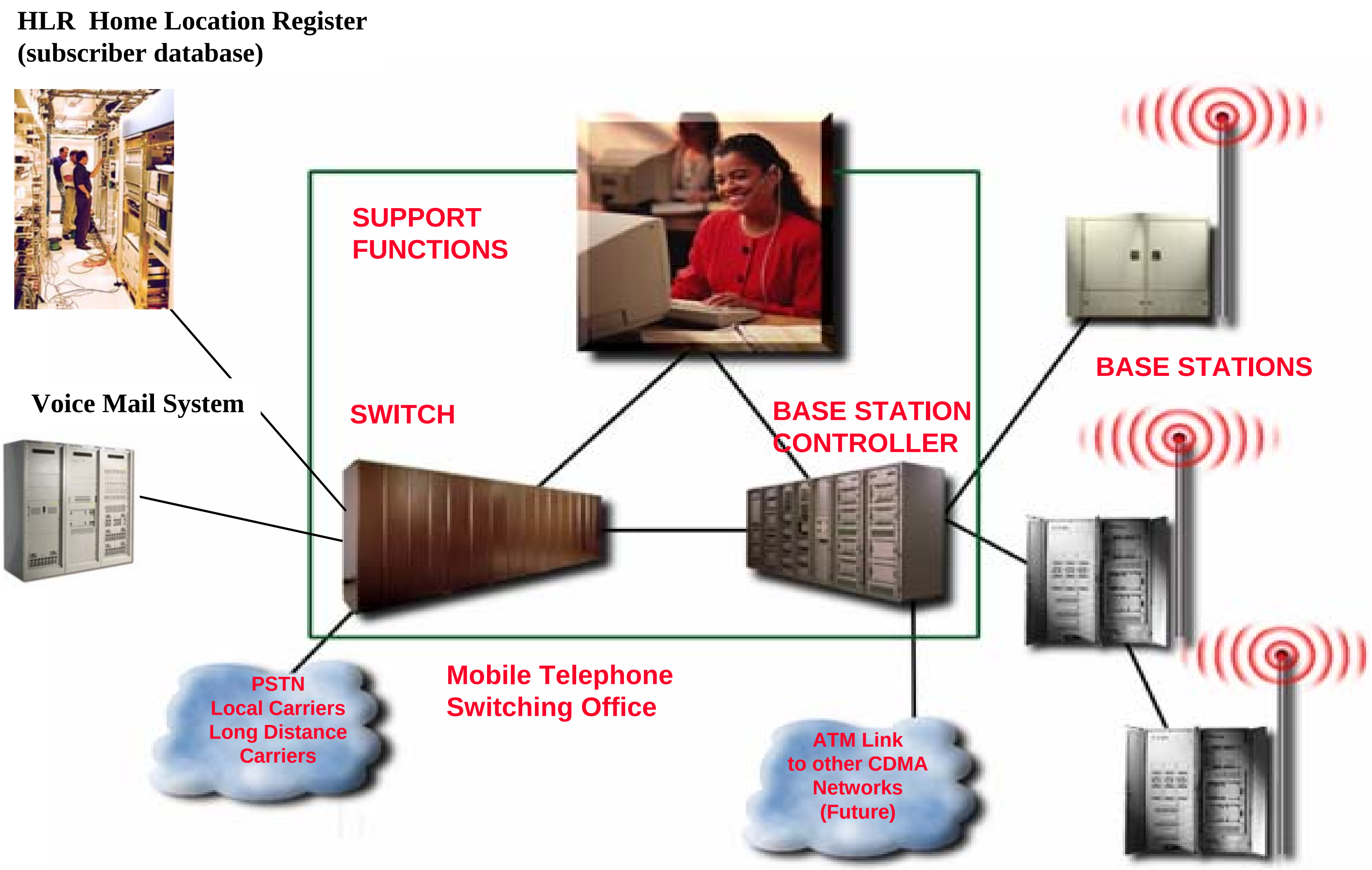
Typical Transmit Gain Adjust



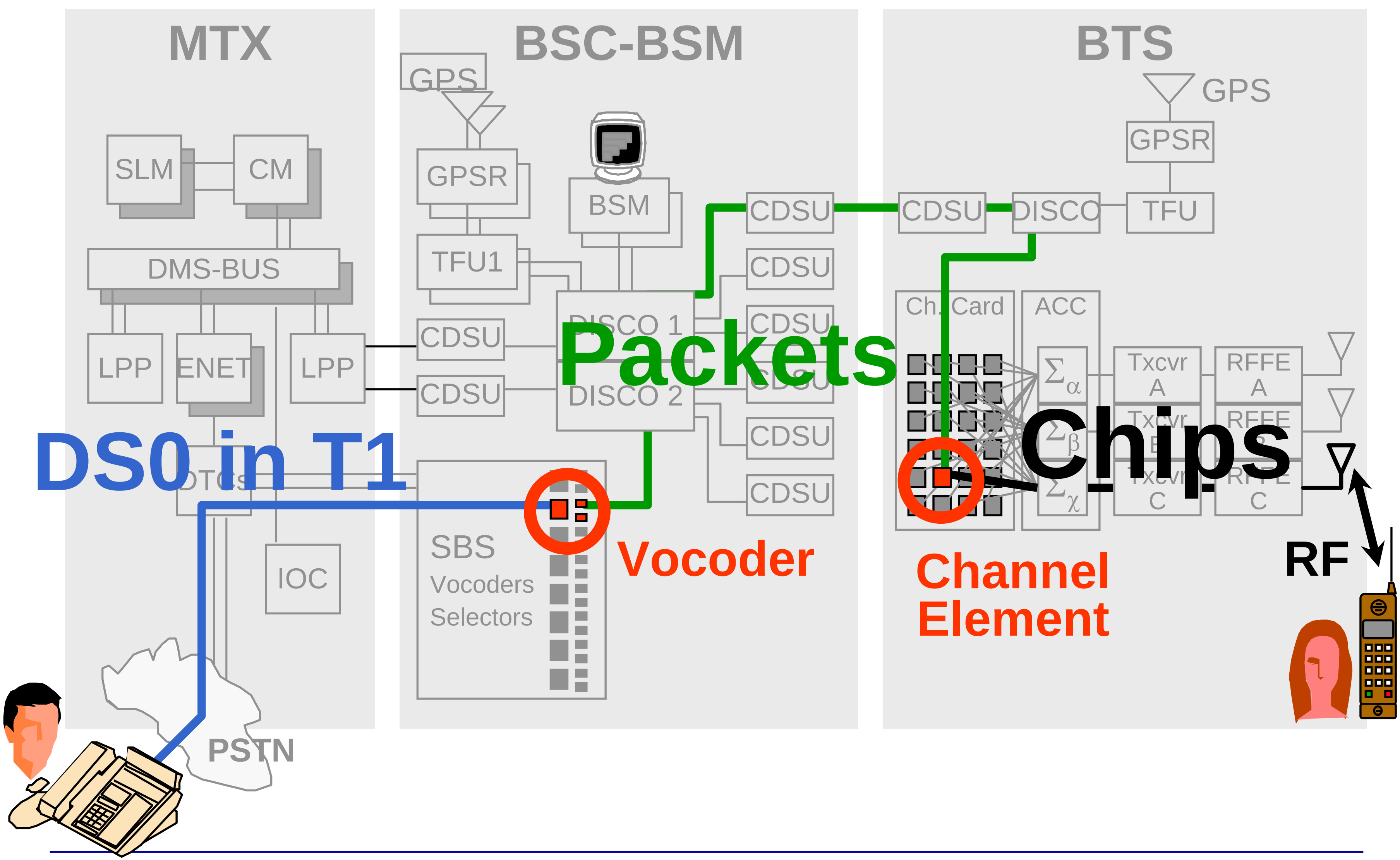
Time, Seconds

CDMA Network Architecture

Structure of a Typical Wireless System



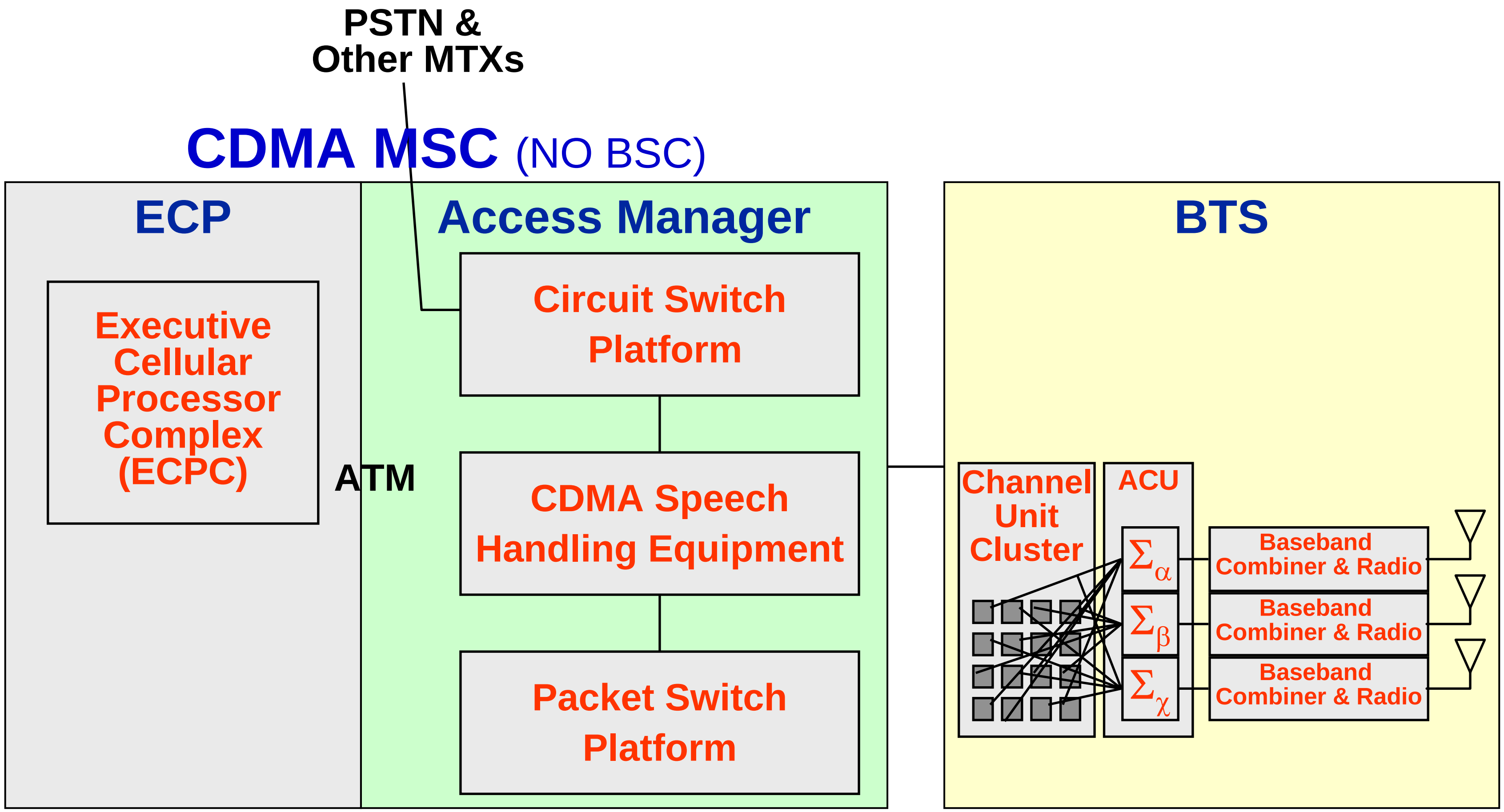
Signal Flow: Two-Stage Metamorphosis



Lucent CDMA Network Architecture

www.lucent.com

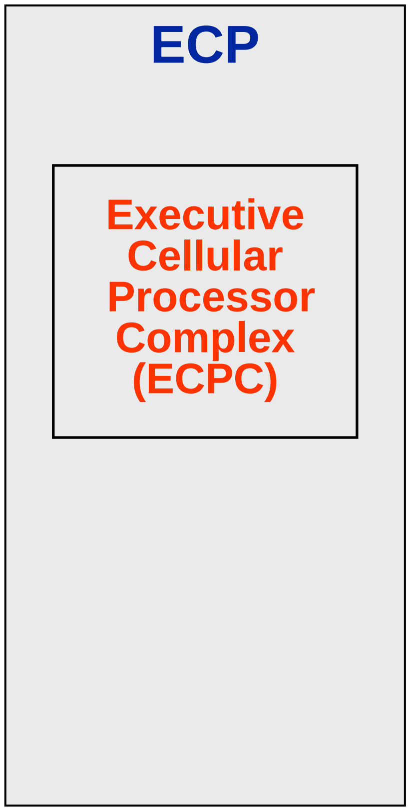
Lucent CDMA System Architecture



Three Sizes of CDMA MSC:
- #5ESS-2000 large markets
- Compact Digital Exchange (CDX) medium market
- Very Compact Digital Exchange (VCDX) small mkts.

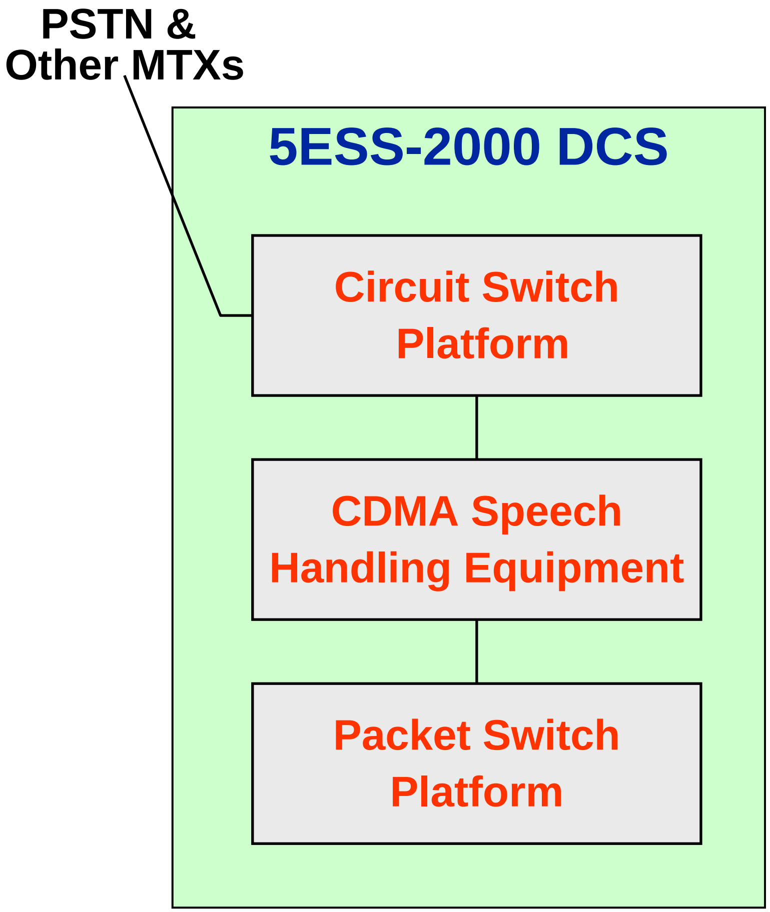
Two Access Manager sizes
- Large: 16 MSCs, 200K BHCA, 222 BTSs, 500K HLR/VLR entries
- Small: 32 BTSs, ~30K subs

The Lucent ECP



- Executive Cellular Processor
- Primary functions
  - Call Processing
  - Mobility Management
    - HLR-VLR access
    - Intersystem call delivery (IS-41C)
    - Inter-MTX handover (IS-41C)
  - Billing Data Capture
  - Calling Features & Services
  - Collecting System OMs, Pegs
- High reliability, redundancy

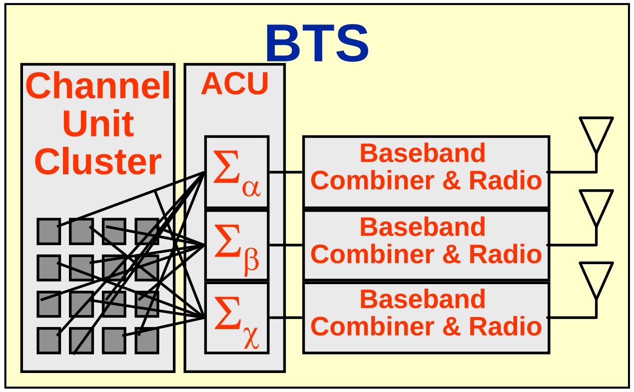
The Lucent #5ESS and Access Manager



- Primary functions
  - vocoding
  - soft handoff management
  - FER-based power control
  - routing of all traffic and control packets
- Scaleable architecture
  - expand speech handlers
  - expandable packet switch

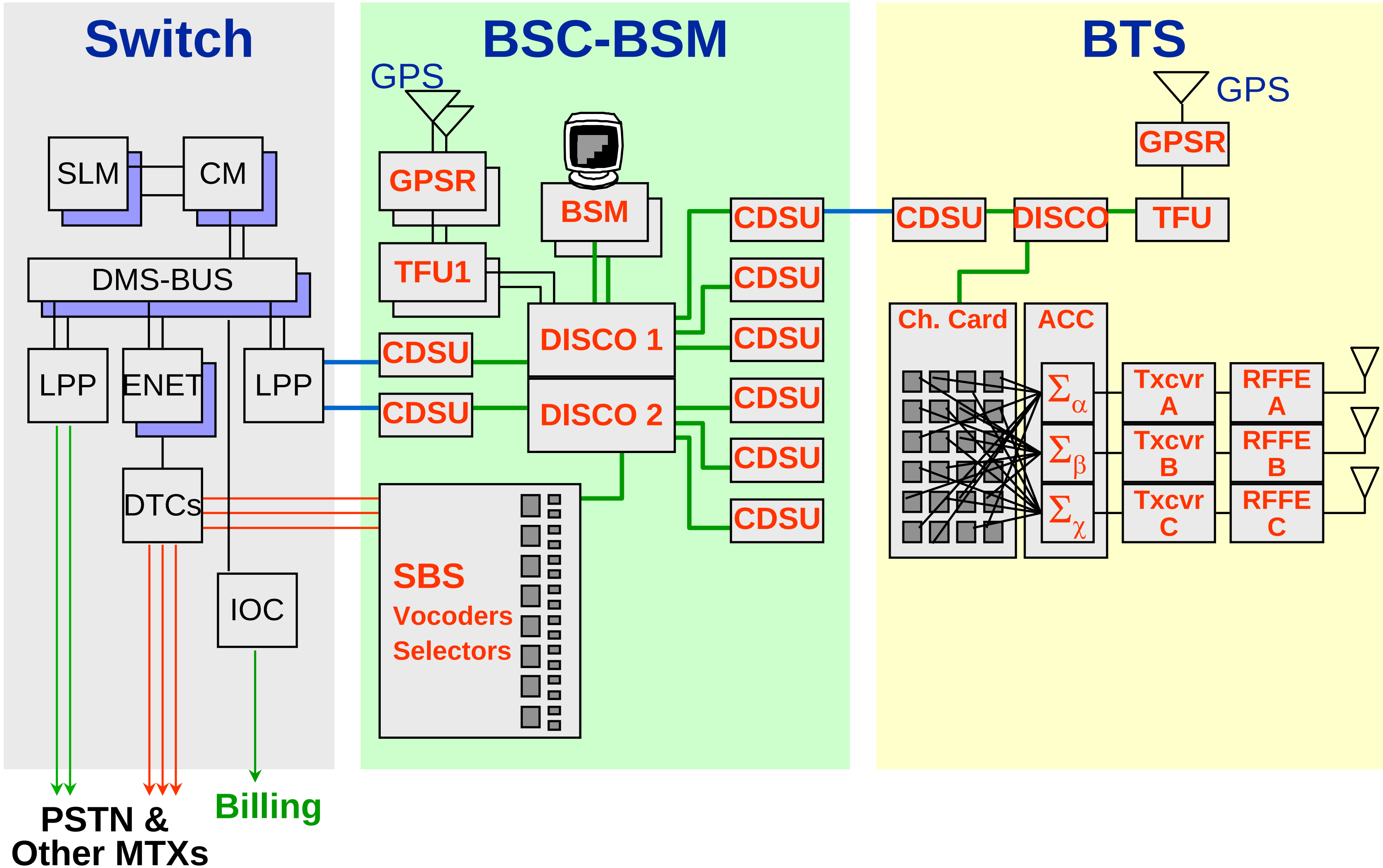
Lucent Base Stations

- Primary function: Air link
  - generate, radiate, receive CDMA RF signal IS-95/J.Std. 8
  - high-efficiency T1 backhaul
  - test capabilities

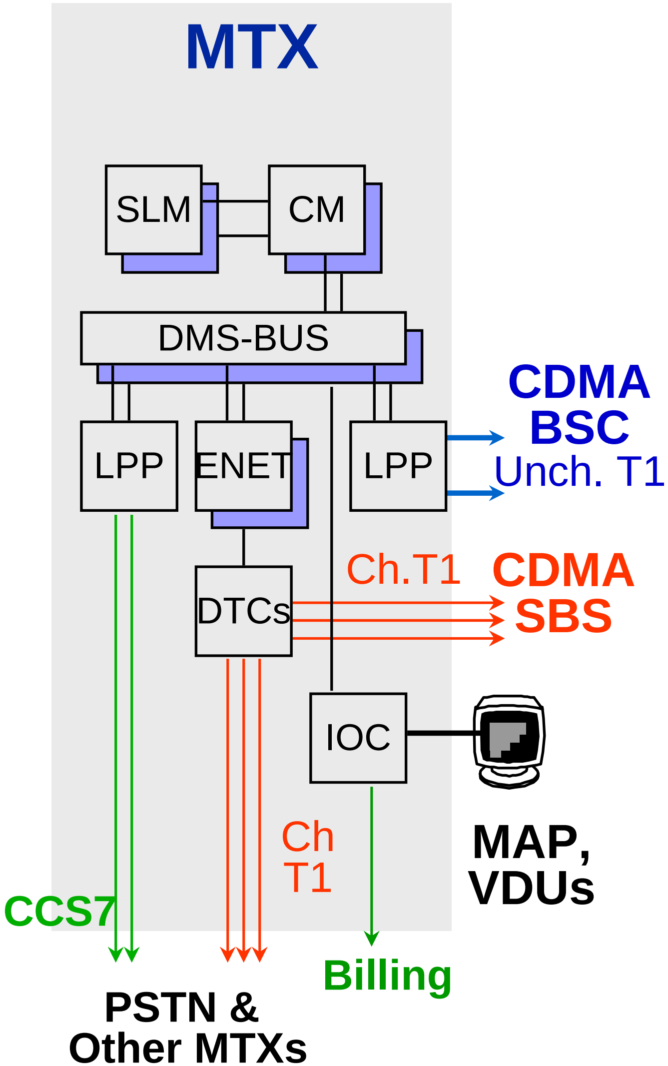


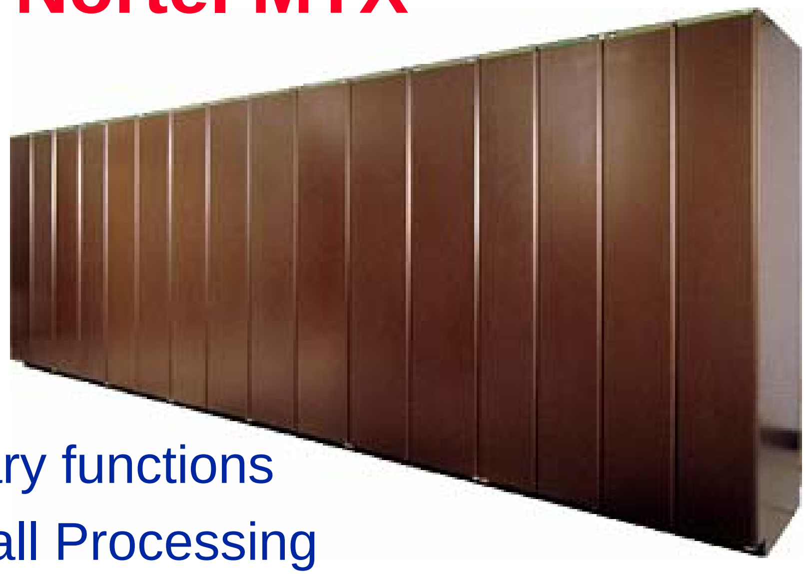
Qualcomm/Nortel/Ericsson CDMA Network Architecture

Qualcomm Early CDMA Architecture



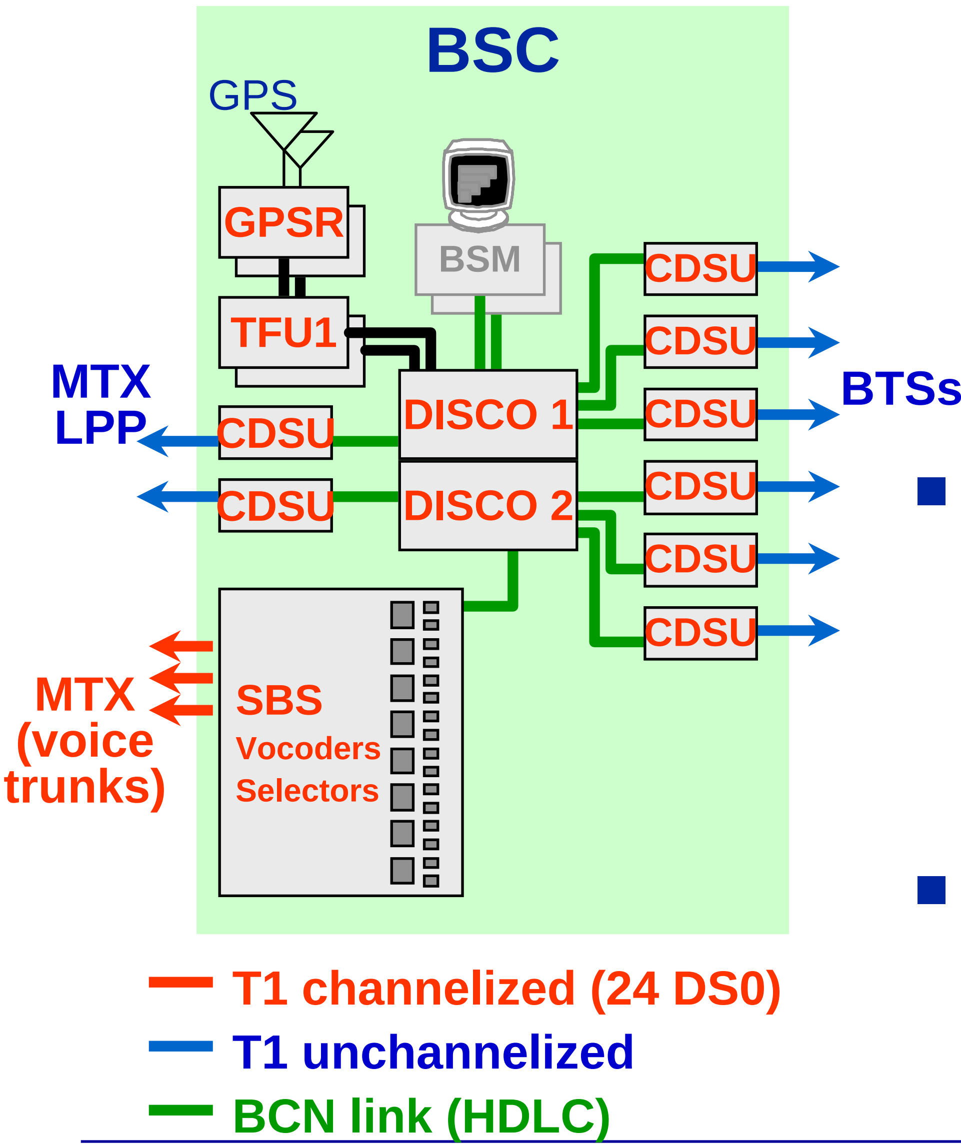
Switch: The Nortel MTX





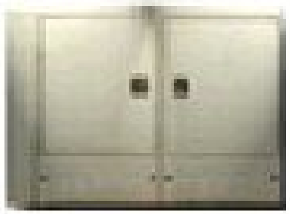
- Primary functions
  - Call Processing
  - Mobility Management
    - HLR-VLR access
    - Intersystem call delivery (IS-41C)
    - Inter-MTX handover (IS-41C)
  - Billing Data Capture
  - Calling Features & Services
  - Collecting System OMs, Pegs
- High reliability, redundancy

The Nortel BSC

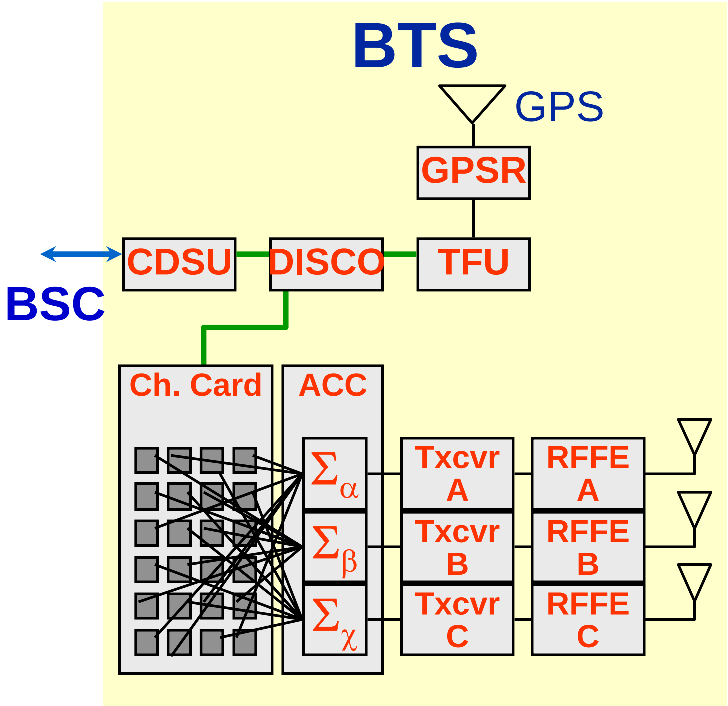


- Primary functions
  - vocoding
  - soft handoff management
  - FER-based power control
  - routing of all traffic and control packets
- Scaleable architecture
  - expand SBS to keep pace with traffic growth
  - expandable DISCO

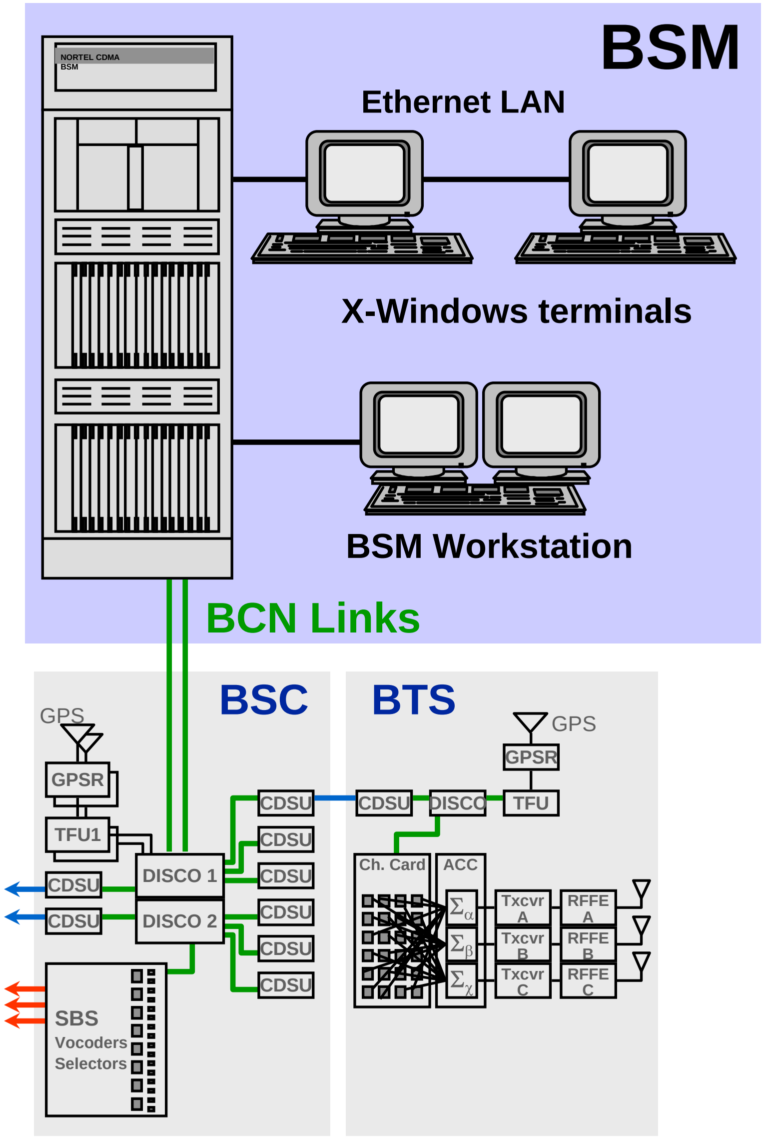
The Nortel BTS



- Base Transceiver Station
- Primary function: Air link
  - generate, radiate, receive CDMA RF signal IS-95/J.Std. 8
  - high-efficiency T1 backhaul
  - test capabilities
- Configurations
  - 1, 2, or 3 sectors
  - 800 MHz.: indoor
  - 1900 MHz.: self-contained outdoor, remotable RFFEs
  - new indoor, 800 MHz. & 1900 MHz. multi-carrier options
  - Metrocell

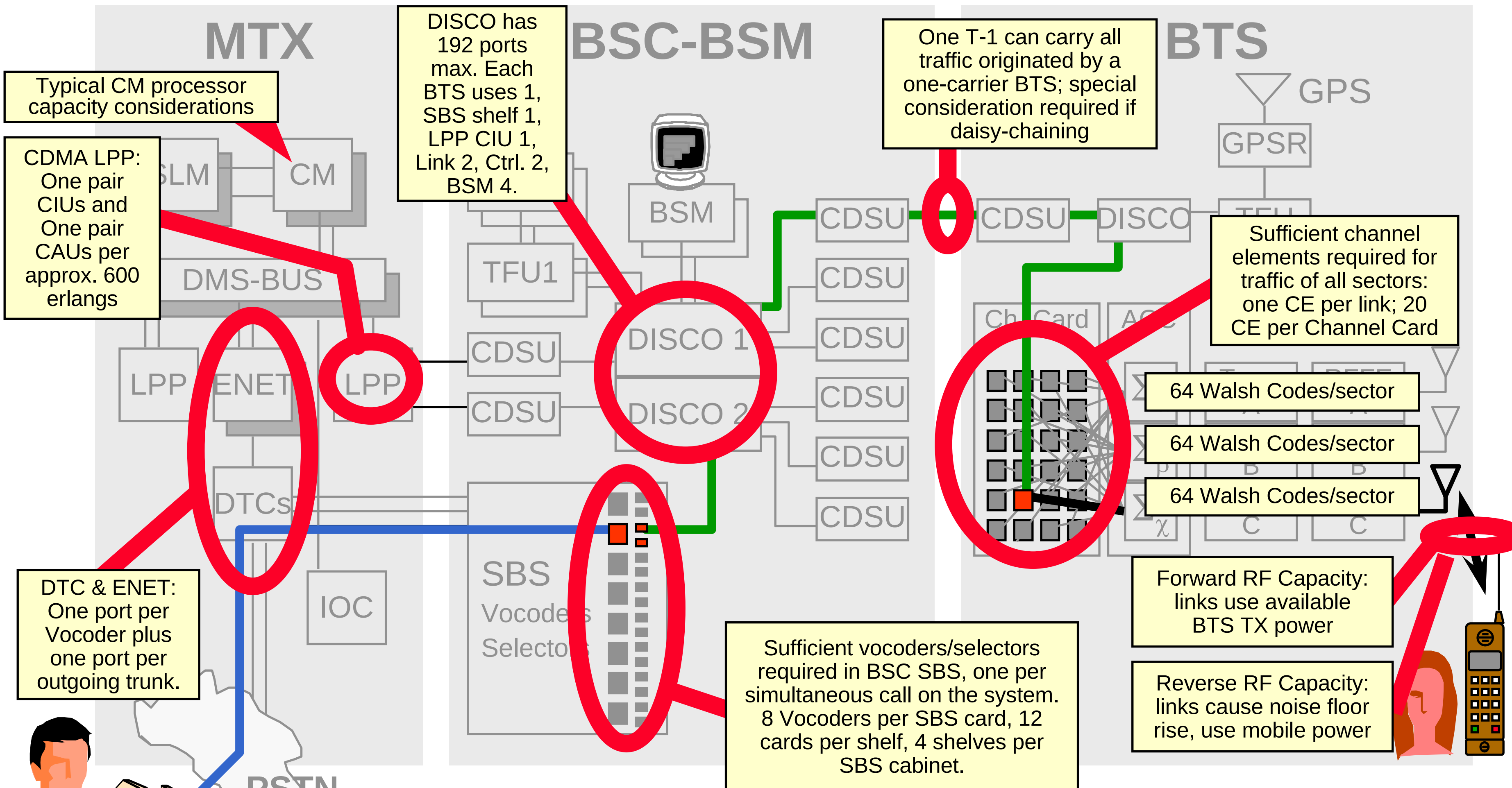


The Nortel BSM



- Base Station Manager
- Primary functions: OA&M for CDMA components
  - Configuration management
    - BSC, BTS configuration and parameters
  - Fault management
    - Alarm Reporting
  - Performance management
    - interface for CDMA statistics and peg counts collection
  - Security management
  - Unix-based

Nortel Operational Capacity Considerations



- 1-2001 Current Product Capabilities:
  - Each BSC can have up to 4 DISCO shelves
    - About 240 sites, roughly 6000 erlangs capacity
  - Each MTX can have up to 2 BSCs